INVESTIGATION INTO THE PROCESSING AND CENTRIFUGATION OF LUNAR AND MARTIAN REGOLITH SIMULANT GEOPOLYMER

by

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DEDICATION

This thesis is dedicated to Linda Louise Lamkin Ely, who always encouraged me to pursue my dreams, no matter how out of this world they may be.

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LIST OF ABBREVIATIONS

Abbreviation	Description
AAS	Alkali Activated Slag
ABS	Acrylonitrile Butadiene Styrene
GCR	Galactic Cosmic Rays
ITZ	Interfacial Transition Zone
LHS	Lunar Highlands Simulant 1
L/S	Liquid-to-Solid ratio
MGS	Martian Global Simulant with Hydrated Clay
NaOH	Sodium Hydroxide
Na_2O	Sodium Oxide
Na_2SiO_3	Sodium Silicate
SEM	Scanning Electron Microscopy
SiO_2	Silicon Dioxide
SP2	Lunar South Pole Simulant 2

ABSTRACT

As human settlement on the Moon and Mars becomes increasingly viable, developing in-situ construction methods using locally available materials like regolith is essential. This thesis investigates the feasibility of producing geopolymer concrete from lunar and martian regolith simulants, focusing on the effects of processing parameters and centrifugation on material strength. Three simulants—LHS-1, LSP-2, and MGS-1C—were tested across varying liquid-to-solid ratios and silica moduli. A novel centrifugal mixer prototype was developed to simulate the effects of artificial gravity on curing geopolymer, with the aim of reducing porosity and improving compressive strength. Results showed that centrifugation can enhance material properties, and that mix design must be carefully optimized for each simulant. This study contributes foundational data and a proof of concept for manufacturing geopolymer tiles in low-gravity environments, supporting the development of durable infrastructure for future extraterrestrial habitats.

1. INTRODUCTION AND BACKGROUND

The desire to explore and live in a faraway place has always been innate within our species. The first humans demonstrated this by migrating from East Africa and continuing with the Polynesians to find remote islands in the Pacific Ocean using wind and stars to guide them. This desire continues to the present day with the stories we tell in our films, the science we study and current space programs that aim to manifest these dreams. One may rightfully question the modern-day motivation of space agencies to explore the unknown and advance science. Unfortunately, inspiring words have always been used as a guise for countries to advance military aims, so cynicism is not unfounded. However, if one is lucky enough to personally meet a scientist or engineer from any space agency, the drive by those employed to explore and send people into space seems genuine and rooted in the curiosity of the unknown that unites all people.

Whether for science, the military, or prestige, nations are clamoring over themselves again to "boldly go where no one has gone before." Space agencies of China, Europe, India, Israel, the United Arab Emirates, the Russian Federation, others and again the United States are sending spacecraft to orbit, land, and move around on the Moon and Mars. This time, the goals are far more ambitious. Governments, companies and universities are developing technologies, not only to send robots, but human beings as well. Now, the stated goals are not only to visit, but to stay for extended periods of time. Just as ancient humans used whatever they found to settle a new area, whether it be soil, rocks or meteorites, we are likely to do the same. Instead of people drying clay in the sun to make bricks for homes, a robot may do this task. By shoveling dust from the ground into a centrifuge to make concrete bricks, it may begin to build infrastructure in anticipation for trailblazers from across the solar system.

This thesis investigates the challenges that the first humans and robots to settle the Moon and Mars may encounter when trying to make geopolymer concrete from the dust that surrounds them. Regolith is the layer of unconsolidated, fine-grained igneous material that blankets the surfaces of both lunar and martian terrains. When mixed with alkali activators like sodium hydroxide and sodium silicate (Dawood et al., 2024, Bondar et al., 2011), this regolith can form geopolymer concrete. When concrete is centrifuged, it can become stronger (Pan et al. 2022). The aim here is to evaluate these principles for a new method of manufacturing building materials from the natural environment. Wherever modern humans settle, from skyscrapers of populated urban centers to sheds next to remote landing strips in tropical rainforests, concrete can be found. Perhaps, one day, with the efforts of this study and many others, the Moon and Mars will be no exception.

1.1 The need for concrete on the Moon and Mars[XS1]

Shelter will be needed for settlement on extraterrestrial surfaces, and transporting building materials is incredibly costly. Therefore, upon arrival at the Moon and Mars, transforming regolith into concrete, humanity's most common building material, and then using that concrete to make shelter is likely to be a pressing task. Shelter would not only serve a psychological purpose, to give people a sense of normalcy during an extended stay, but there are several significant dangers from which they will need reliable protection. Radiation, a grave concern for space travelers, is commonly contained by concrete at nuclear power plants on Earth to protect the people that live around them. This can also be an option for helping to protect people on the Moon and Mars from radiation that comes from above whether it be Solar or Galactic Cosmic Radiation. 100 millisieverts (mSv) is commonly agreed to be an acceptable amount of radiation exposure for

workers to clean up a nuclear accident (Boscolo et al. 2022). The annual radiation exposure on the Moon can be up to 900 mSv (Reitz et al. 2012), with Mars reaching up to 320 mSv (Guo et al. 2021). 2.5 meters of sulfur concrete, or 1.5 meters of solid basaltic rock are needed to shield humans to 100 mSv on Mars because of the Galactic Cosmic Rays (GCR) that occur on Mars at solar minimum. Earth's Moon is closer to the sun than Mars, so the solar radiation risk is far more severe which requires more layers of protection. Researchers recommend various combinations of materials including 150 cm of regolith compressed from 1.6 g/cm^3 to 4.0 g/cm^3, 3 mm of aluminum and 5 cm of polyurethane (Akisheva et al., 2021). Normally, humans need shelter for protection from the elements, on the Moon and Mars, in some regards, humans will need them for the lack thereof. On the Moon there is virtually no atmosphere with 10^5 -10^7 particles/cm^3 compared to the 10^{19} particles/cm^3 on Earth (Mendillo, 1999). On Mars, the average atmospheric pressure is about 0.6% that of Earth (Banfield et al., 2020). Exposure to atmospheric pressures this low would result in a fatality within minutes. In addition to protecting humans from the vacuum of the surface on both solar system bodies, concrete can help to protect from problematic dust.

Mars experiences seasonal planet-wide dust storms, driven by atmospheric circulation resulting from carbon dioxide sublimation at one pole and deposition at the other. While the dust on Mars is not as jagged and sharp due to aeolian erosion, it is still very harmful to humans in many ways. If inhaled, fine silica, basalt, pyrite, beryllium, gypsum and nanophase iron oxides lead to lung disease for which there is no cure. Arsenic and cadmium detected in Martian meteorites are associated with significant health risks, with arsenic acting as a carcinogen that can cause neuropathy and cadmium contributing to kidney disease. For chronic exposure there is no cure for either. The small size of dust particles, along with the electrostatic and magnetic qualities

make contamination in living quarters practically inevitable. Not only does the fine particle size of dust on the Moon and Mars facilitate ease of entering spacecraft and habitats, but it also makes it easier for these grains to enter the human body and cause health problems (Wang et al., 2025).

The Apollo astronauts, despite their brief contact with the Moon's surface when reentering the lunar module as seen in Figure 1, had watery eyes, decreased vision, throat irritation and a cough that affected performance. Thankfully, no long-term health effects have been reported as symptoms improved within 24 hours afterwards. Prolonged exposure, however, will continue to be a challenge as respirated jagged, fine particles like those seen in Figure 2 are likely to cause silicosis. Silicosis is a well-documented lung disease which results when silica dust is inhaled and lodged in the alveoli of the lungs which leads to fibrosis.

Figure 1: Lunar regolith adhering to the astronaut Gene Cernan's spacesuit during the Apollo 17 mission NASA Public Domain (Pohlen et al. 2022)

On Earth, nanoparticles ingested can accumulate in cellular cytoplasm and lead to colon cancer and Crohn's disease. If dust is repeatedly exposed to the eyes, corneal injury is likely. Slight conjunctival erythema and edema resulted from simulated tests performed by NASA following reports of eye irritation by lunar astronauts (Pohlen et al. 2022). The compounding effects of all these health hazards, along with the psychological stress of being in a new environment could impact fertility and lead to birth defects of the first humans not born on Earth. If long term settlement is the overarching goal of space agencies' collective will to push further into space, these problems should be mitigated to protect humans from the harsh space environment.

Figure 2 High-resolution imaging of lunar surface particles collected during Apollo 17 operations, captured via scanning electron microscopy. NASA Public Domain (Pohlen et al. 2022)

Concrete is a primary candidate for this need. Concrete is a strong, versatile, and reliable building material. It can be manufactured from minerals that are plentiful in the geology of most countries, and it can be molded into almost any shape imaginable. Being the most abundantly used material by humanity after water (Waters et al., 2018), it is logical that humans would continue to employ this material wherever we settle. People have mastered the manufacture and use of concrete on Earth. However, despite the stated intention of space agencies to establish a permanent presence elsewhere, we have yet to make and use anything resembling concrete anywhere but

Earth, except for the International Space Station (ISS) (Moraes Neves et al., 2019).

Making ordinary portland cement off world would require either shipping large quantities of cement through space or heating regolith up to 1700°C on the Moon and Mars. There is a promising alternative that allows the use of regolith to be formulated into concrete without extensive processing of the parent material. Geopolymer is a type of concrete that can potentially be made by mixing regolith with aqueous sodium hydroxide and sodium silicate. Unfortunately, despite the promise of this building material and the hundreds of kilograms of lunar material in vaults at Johnson Space Center in Houston, researchers have yet to produce geopolymer with actual regolith on Earth or in reduced gravity.

1.2 Issues with trying to replicate Moon and Mars conditions

Inevitable limitations must be considered when analyzing results from this study and using them as a guide for robots, astronauts, cosmonauts, taikonauts or anyone making concrete on the lunar and martian surface. Regolith simulant comes from Earth and these experiments are taking place on Earth. Actual regolith from the Moon is inaccessible to the broader scientific community with rare exception and at the time of writing, no human has ever had access to regolith on the surface of Mars. The Moon and Mars have low gravity, no liquid water or life, and lack atmospheric pressure like Earth's. These conditions among others will change the nature of fragments from the planetary and lunar crust. Their surface also formed through unique geological processes over billions of years, many of which are still not fully understood. As a result, it is not possible to create regolith simulants on Earth that perfectly replicate actual lunar or martian soil. The attributes of simulant from a supplier are sometimes inconsistent between shipments. Particle size may vary substantially, which is of paramount importance when formulating geopolymer as

surface area greatly affects reaction kinematics. It has not been tested whether variations in atmospheric pressure or humidity at different elevations and geographic locations on Earth would significantly influence the chemical reactions observed in these experiments. In off-world scenarios, reduced gravity and the specific air composition within pressurized habitats on the Moon or Mars may also impact processing in ways that are not yet fully understood.

The lack of actual extra-terrestrial raw material accessible to concrete researchers slows down development. To date, the only sample of concrete that has been made of actual regolith from the surface of the Moon is in a secure vault at Johnson Space Center in Houston, Texas (Lin et al., 1992). This concrete sample is not geopolymer which is the focus of this study, it is ordinary portland cement to which sand was added for workability. The rest of the hundreds of studies regarding concrete on other worlds use regolith simulant. Regolith simulant consists of volcanic soils from Earth that closely resemble extraterrestrial regolith, as much as is economically feasible to gather, process and sell to researchers. The discrepancy between the two will be expanded upon in greater detail but the fact remains that there is a distinct difference between regolith and regolith simulant. Until researchers have sufficient quantities of actual regolith from the Moon and Mars to run tests, all published research using simulant is conjecture at best. Concrete is studied all over the world with an extensive number of changing variables for different settings and conditions. Humankind is very reliant on this material, so it is appropriate that we understand it fully. Importing enough actual regolith from the Moon and Mars to rival concrete studies undertaken globally at universities and companies even for one day is impossible with current technology.

Studying the effects of centrifugation at different locations around the solar system without going to these places has its limits as well. All tests conducted on Earth are subject to Earth gravity,

of which Mars has one third and the Moon has one sixth. The only way to reduce gravity on Earth for more than a few seconds is a parabolic flight. This can only offer minutes of reduced gravity, which is not enough time to significantly influence the microstructure of a concrete sample. To centrifuge concrete samples on Earth subjects them to centrifugal force in addition to Earth's gravity, which is not what astronauts would experience when making the first samples of in-situ lunar and martian concrete. The intention would be to simulate or exceed Earth gravity while on the Moon and Mars so that through centrifugal force one might make concrete that would be equally as strong as if it were made on Earth. Centrifugation speeds sufficient to overcome Earth's gravity for research purposes will differ substantially from those required in lunar or martian environments, as the necessary speed depends on material behavior. Simulant-based parameters for Earth gravity will not directly translate to the Moon or Mars due to differences in regolith cement slurry flowability, adhesion, and density. Furthermore, variability in the consistency of regolith simulants, even across different batches from the same supplier, can pose challenges for reproducibility, potentially hindering other researchers from replicating experimental results. The data gathered in this study revealed discrepancies between two different orders of Lunar Highland Simulant sourced from Space Resources Technologies ("Lunar Highlands," 2025) but this occurrence in unlikely unique to this supplier.

Challenges remain for transferring this knowledge to new worlds and producing it in a space environment but a proof of concept is necessary for researchers to make any progress. While errors are inevitable in developing technologies for extraterrestrial settlement, it is preferable to address them in controlled Earth-based laboratories. The alternative is to encounter unanticipated problems during lunar or martian missions, where corrective measures are limited and human lives

are at risk. As always, with any academic study, there are constraints to time, money and resources that limit the scope of what the author might have wanted to accomplish. These limitations don't negate the fact that within this work are data from the world's first centrifuged, lunar concrete tiles and ASTM standard testing specimens. Despite our best efforts, the conditions for studying geopolymer on Earth are likely to differ so radically from the conditions on the Moon and Mars that we will never know until we go. In the meantime, it is essential for researchers to advance the science and engineering of space settlement to maximize crew safety and enhance the likelihood of mission success upon arrival.

1.3 NASA initiatives and NASA MINDS

In 2017, the National Aeronautics and Space Administration, (NASA) launched the Artemis program to centralize and direct efforts to reestablish a presence on the Moon, with long term goals that include a permanent base. A litany of government programs, public-private collaborations and university competitions stemmed from this program to develop the engineering expertise that would further these aims. As part of the NASA Artemis program, large payload rockets are planned to land on the Moon to establish a crewed research facility. An ambitious addition accompanying this Moon base is the lunar gateway space station that is planned to revolve above in a near-rectilinear halo orbit. Following these efforts, the United States is planning to establish a crewed presence on Mars. The very nature of the distance traveled, along with the energy required to arrive, necessitates a longer stay. Building materials will be needed for a variety of applications including landing pads, pressurized structures for habitation, infrastructure for harvesting and transferring materials, and any number of unforeseen needs crucial for living on the Moon and Mars. A project within NASA, Moon-to-Mars Planetary Autonomous Construction

Technology (MMPACT) is tasked with advancing the technology of building extraterrestrial structures with an emphasis on in-situ resource utilization. This program identifies the types of structures needed, potential building materials, and roadmaps to build structures with these materials.

It is noteworthy to mention that at the time of writing, halfway through the 2020s, no exact dates have been announced to launch the first components of any crewed extraterrestrial base, be it lunar or martian. U.S. Presidents, through NASA—which operates under the executive branch—have a longstanding history of announcing ambitious space initiatives that frequently remain unrealized. When government initiatives falter—often due to shifting priorities between administrations—the private sector and academic institutions can provide continuity by advancing the technologies necessary for future space settlement, regardless of political timelines.

An important example of public-private achievement is Firefly, a Central Texas based company, which completed the first successful landing of a privately operated spacecraft on an extraterrestrial surface with the Blue Ghost lander's mission to the Moon. During a single lunar day, from March 2 to March 16, 2025, the Blue Ghost Mission 1 transported ten NASA science and technology payloads to the Moon's near side as part of the CLPS (Commercial Lunar Payload Services) initiative. Each payload activated successfully, and the lander returned 119 gigabytes of data to Earth ("BBC News", 2024; "NASA news-release" 2024). An example of a public-private partnership initiative regarding concrete in space has been with another Central Texas based company ICON, which specializes in the additive manufacturing of concrete. In 2023, this company printed a 1,700 square foot simulated martian habitat at Johnson Space Center in Houston, Texas for the Crew Health and Performance Exploration Analog (CHAPEA) program.

The purpose of this facility, in addition to demonstrating concrete additive manufacturing construction, was to study the crew's ability to live and work together for a year while simulating being on Mars ("NASA Centers and Facilities," 2022). This collaboration happened in part from ICON's success in the 3D printed habitat challenge in 2019 which pit architectural firms and universities against one another to develop additive manufacturing in space ("NASA Centers and Facilities," 2019). These structures had to endure freeze thaw tests, a simulated meteor strike, and a pressure differential seal test.

Another university competition is NASA MINDS, which stands for Minority University Research and Education Project (MUREP) Innovative New Designs for Space (MINDS). Texas State University, as a Hispanic Serving Institution, first participated in 2020 as the Bobcat CaerusCrete team. The group later investigated lunar concrete from a civil engineering perspective, using fiber reinforcement to strengthen regolith simulant concrete which resulted in the team winning first place in 2023. The 2024 Bobcat CaerusCrete team, led in an advisory role by this thesis's author, won second place in this competition for prototyping a centrifuge for a lunar concrete mixer. The premise of the project was to reduce the porosity of concrete cured in a low gravity environment, inspired by the high porosity of concrete cured on the ISS (Moraes Neves, 2019). Unfortunately, the team was unable to demonstrate a mechanically functional machine before the contest's end date, but the proof of concept was demonstrated. The 2025 team did in fact demonstrate a functional machine, again winning second place nationally, but as of writing the team's prototype has yet to mix concrete.

This thesis builds on the prior work of the 2024 Texas State NASA MINDS project by investigating the effectiveness of mix designs with alkali activator and lunar regolith simulant. The

hypothesis of a compressive strength increase from centrifugal force exerted on lunar regolith simulant geopolymer was tested. Further advancements also were made in developing a prototype centrifugal concrete mixer. For this study, concrete tiles, a potentially useful product on the surface of the Moon, were manufactured in a controlled manner from lunar regolith simulant geopolymer using a drill press via mixing and rotation into molds. The strength of the material in the form of cubes was compared to geopolymer concrete mixed in the same batches but not undergoing any kind of centrifugal treatment. By integrating materials science to assess the printability of alkali-activated regolith simulant slurry, civil engineering to evaluate compressive strength, and manufacturing engineering to produce concrete tiles, this thesis seeks to support the advancement of construction technologies for future human settlement on the Moon and Mars.

2. LITERATURE REVIEW

The cost of bringing materials to other worlds is astronomically high, as researchers estimate the cost of propellant alone to bring one kilogram from the Earth to the Moon for a crewed mission can be $18,000-$36,000 (Miyajima, 2022). The cost disparity between transporting mass to Mars versus the Moon is immense due to a range of contributing factors. The vast distance to Mars, the operational complexities of interplanetary travel, and the challenge of decelerating safely through the Martian atmosphere represent just a few of the significant and costly obstacles that remain unresolved. Therefore, the cost per kilogram of bringing large shipments to Mars for this purpose will inevitably be significantly more. Further complicating matters is the fact that accurate cost estimates are ultimately uncertain as they depend on technologies like orbital refueling that as of writing have yet to be demonstrated. Assuming it is eventually possible to bring humans to Mars, as this thesis clearly does, space agencies will have to minimize the mass to be transported. Consequently, in-situ resource utilization represents the most viable approach for sustaining long-term habitation on the Moon and, more critically, on Mars. The potential advantages are substantial and may ultimately determine the feasibility of future missions. If astronauts are able to produce bricks and concrete from locally available regolith, they can avoid the need to allocate spacecraft volume, expend fuel to launch construction materials from Earth, or rely on additional funding to transport such heavy resources. The successful application of these materials may not be immediate, as initial crews will need to conduct on-site testing to validate their strength, durability, and practicality prior to full-scale implementation. However, the possibility alone warrants further investigation, so the literature review that forms the foundation of this work will focus on utilizing regolith to make concrete.

2.1 Extraterrestrial materials and concrete

There are several methods for making extraterrestrial concrete with regolith other than geopolymer, the focus of this thesis. These methods include calcium aluminate cement, magnesia silica concrete, polymer concrete and sulfur concrete. Calcium aluminate concrete can be produced in a similar manner to how cement is made on Earth, by subjecting lunar anorthosite to a high pressures and temperatures, 1727°C and above. The process is water intensive, but researchers have introduced a dry-mix/steam injection method to reduce water usage for space applications. This practice involves mixing aggregate and cement and subjecting the dry mix to high pressure and temperature steam. The mix is then added to aggregate, water, and sand for mixing, and then cured. Dry mix/steam injection can result in faster curing times, reduced porosity and increased compressive strength. This is unfortunately energy intensive but requires less cement, is relatively unaffected by low temperatures or near vacuum air pressure and can reach a relatively high compressive strength of 69-120 MPa (Wu et al., 2024). This method has been demonstrated for lunar, but not yet martian regolith simulant. Magnesia silica concrete is another candidate for martian building materias. First, through the hydrolysis of olivine one can derive magnesia (MgO). Then, by adding silicon dioxide (SiO_2) along with fine aggregate, a dry, even solid particulate mixture can be attained. One can then add water and coarse aggregate before stirring evenly and depositing the resulting slurry into a sealed mold. A compressive strength of 18-87 MPa can be obtained, and material preparation energy consumption is low, however this concrete is prone to volume expansion as it cures, which increases the likelihood of defects (Hu et al., 2022).

Polymers provide a waterless method for producing regolith-based materials, such as resin, polymer cement, or impregnated concrete. Polymer based concrete has good radiation shielding

ability, and the compressive strength can range from 3.25 to 71 MPa. It can be light weight and is easy to process. For lunar concrete, polyethylene or polypropylene pellets would be mixed with regolith, heated to 230℃ and cured to form a resin-matrix composite and then placed in a mold. There is no chemical change to the regolith itself, but it is structurally bound to the polymer. For most extraterrestrial applications, however, this method would not be practical because a substantial amount of polymer mass would need to be brought to the site. Researchers estimate a necessary proportion would be 10% polymer and 90% regolith by mass. Materials would be cemented together by the polymer regardless of the chemical makeup of the regolith. If exposed to temperatures near what melted the polymers during processing, the material would become plastic again (Lee, T.S. et al., 2015).

Sulfur concrete is another method of solidifying regolith that can be utilized on the Moon or Mars, which has the advantage of utilizing naturally occurring sulfur which can be mined on both celestial bodies. Refined in the absence of water, this potential building material has high early compressive strength and is composed of only sulfur and regolith. After finding an outcropping of regolith high in sulfur, the mined material can be heated to 1100℃ to extract the sulfides and sulfates. Then, the user can evenly mix sulfur and regolith. Researchers have found a sulfur content of 45% to be optimum for strength and workability. At this ratio, the compressive strength was found to be 35 MPa, and when raised to 55%, the resulting compressive strength declined to 26 MPa. When magnetite is present in martian regolith, a microwave oven may be used. Silica and fibers can be added to improve strength, but there are attributes to this material that can make it undesirable for many applications. When exposed to a vacuum and temperatures above 120℃, the material can sublime. This is very unfortunate for use on the Moon as

temperatures on the lunar equator can reach 120℃ and the surface has a near vacuum. In addition, sulfur concrete is sensitive to temperature cycling. If the temperature cycles between a range of 21℃ and 191℃, the strength can decrease by 20%. After 7 days at room temperature sulfur concrete can experience a mass loss of 60% and a reduction of compressive strength of 59%. This would not only disqualify the material from use in equatorial regions of the Moon, but it would also be insufficient to serve as a concrete in interior habitats where humans enjoy the atmospheric pressure of Earth. Furthermore, it remains uncertain whether sulfur deposits in sufficient concentrations will be accessible near construction sites, or if the material would need to be transported over long distances across the surface (Rahim 2021).

It is possible that all of these methods of concrete will be used for different applications on different locations, by different space agencies. Geopolymer, on the other hand, chemically changes the regolith itself into a binder and can form concrete on both the Moon and Mars (Hu et al., 2022). The temperature at which geopolymer can be cured is lower than 100℃, which is far less than the 1727℃ needed to refine calcium aluminate, the 1100℃ needed to extract sulfur from raw ore or the 230℃ needed to cure the resin matrix composite of polymer concrete. Other than regolith, geopolymer production requires only sodium hydroxide and silica powders that can be dissolved in water. All of these compounds contain elements available on both the Moon and Mars (Slabic et al., 2024). If these reagents are not mined and refined from local resources, the alkali activators must be transported and replenished. The water, however, does not remain chemically bound to the concrete and can subsequently be recovered during the curing process to be reused indefinitely. For these reasons, geopolymer is a very promising building material on the surface of these worlds.

2.1.1 Regolith vs. simulant

Regolith is defined as unconsolidated material covering bedrock and is simply smaller pieces of the celestial body, which for the purpose of this study is Mars or Earth's Moon. This can include rocks, gravel, dust, or extremely fine particles (Fackrell et al., 2021). There are, of course, many differences between actual regolith and regolith simulant, starting most importantly with their origins. Companies that produce simulant, like Space Resource Technologies, work with NASA to ensure a standard of quality of regolith simulant. However, it is a product made with a profit motive from Earth materials, to mimic a priceless commodity from space. This product was prepared for and marketed to scientists, engineers and entrepreneurs doing a wide variety of research across multiple disciplines. In certain studies, chemical properties such as pH, volatile content, and precise mineralogical composition may be of greater significance. For other studies, accurate physical properties, such as particle size distribution, thermal conductivity, porosity, and grain morphology are more critical to achieving their research objectives. Different science and engineering disciplines may benefit from accurately replicating the mechanical properties of the Moon's unconsolidated surface material such as shear strength, cohesion, angle of repose, and compressibility to test their specific hypotheses. All these properties must be carefully balanced, and a standardized protocol must be established to ensure consistency among shipments. This is critical, as it is difficult to reach scientific consensus if researchers cannot reliably reproduce experimental results using the same material in different laboratories around the world. Once a standard for the simulant to be produced is established, processing methods must be applied consistently. Each step in the production process should be evaluated through a cost–benefit analysis to determine whether increased authenticity justifies the additional effort. Eventually, a

price point is selected that strikes a balance in between the two extremes of “sufficiently representative to be pragmatically economical” and “as representative as the capabilities of human engineering can muster.” Ultimately, it is impossible to create a sample that perfectly replicates lunar or martian regolith, as the geological and environmental processes that formed these materials over billions of years are unique to their respective environments.

Despite these challenges, actual fragments from the surfaces of the Moon and Mars are available for study on Earth, enabling scientists to infer the properties of the martian crust and to develop simulants that closely replicate their characteristics. Numerous martian meteorites, some even available for purchase (Ward’s Science, 2025), were violently ejected from their extraterrestrial origins, traversed interplanetary space, and endured intense heating during atmospheric entry before landing on Earth's surface. Aside from lithic ejecta, no martian regolith to date has been analyzed with the investigative capability of laboratories on Earth. Researchers must rely on data derived from these meteorites and data captured from instruments on probes, rovers and landers on the red planet. Unlike the Moon, Mars has hosted multiple mobile miniature scientific laboratories operating continuously for several years. The Spirit, Opportunity, Curiosity, and Perseverance rovers have each conducted a broad range of in situ scientific analyses across diverse Martian terrains. Although these rovers lack the extensive analytical capabilities available to researchers on Earth, they have nonetheless contributed significantly to the planetary science community’s understanding of Mars and its regolith.

Because of NASA’s Apollo program in the 1960s and 1970s, there is an incomparably larger amount known to science about lunar regolith, than martian regolith. There is actual extraterrestrial regolith in Earth laboratories, but it is not open to the public. The vast majority of

lunar regolith on Earth resides under strict government control by space agencies of the only countries to have returned samples from the Moon, the United States, the Russian Federation, and the People's Republic of China. While Johnson Space Center in Houston, Texas ("Lunar Samples Vault," 2016) and the Vernadsky Institute in Moscow, Russia ("The Museum of Extraterrestrial Matter," 2022) maintain lunar sample displays for public viewing, access to specimens for scientific research is restricted to highly secure laboratory environments and limited to researchers with specialized security clearance. Most Chinese lunar samples are housed in similar circumstances at the China Academy of Space Technology, with the China Aerospace Science and Technology Corporation in Beijing ("China's Chang'e-6," 2024). Although actual lunar regolith is not available for use in this study, there remains the possibility that future experiments could employ authentic regolith to validate findings. Such verification would be essential before astronauts depend on the results of any study involving lunar regolith simulant.

2.1.2 Lunar regolith and simulant

The lunar regolith that the Apollo astronauts brought back to Earth was found to contain plagioclase feldspar, similar to bytownite and anorthite, and traces of pyroxene. As depicted in Figure 3, it is theorized that the Moon formed as a lunar magma ocean with plagioclase feldspar floating to the top and denser olivine and pyroxenes sinking to the bottom. The plagioclase feldspar accumulated in anorthosite and dunite which is predominantly olivine settling in smaller amounts. Frequent impacts from meteorites continually bombarded and eventually fractured the crust over billions of years. With the interior of the satellite still heated by radioactive decay, pressurized basaltic magma began to rise through these fractures causing volcanic flooding. This explains the discoloration in the Moon that we see in the night sky. The lighter highland areas are the older

crust and the darker areas are the younger lunar mare, where the molten interior of the planet rose to the surface. Meteorite impacts continue to bombard the Moon, progressively fracturing its surface rock into increasingly finer particles.

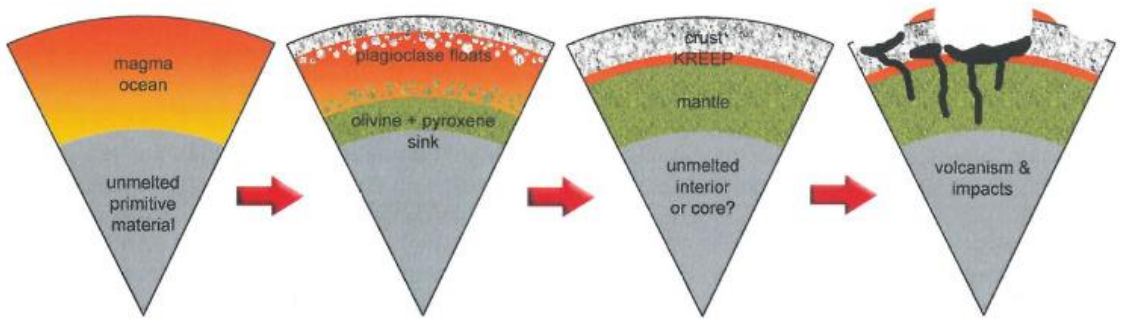

Figure 3: Hypothesis of Lunar surface formation (Slabic et al., 2024)

In the absence of natural erosive agents such as water, vegetation, fauna, or microbial activity, the resulting regolith remains composed of sharp, angular fragments that closely resemble their parent material (Slabic et al., 2024). The particle distribution consists of subangular to subrounded particles with a relatively high porosity (Kobaka et al., 2023). It is, however, not a completely homogenous material. Regolith on the Moon varies in quality depending on geography and based on samples that have been retrieved from the Moon. For lunar highlands regolith, scientists use a ternary diagram, seen in Figure 4, to help systematize the material. Based on these retrieved samples, there are a variety of simulants that researchers use to replicate this geographical variation. Compared to terrestrial simulants, actual lunar regolith is characterized by a higher concentration of fine particles, more angular grain morphology, and diminished particle cohesion. (Lin et al., 1992). Shear strength tests on lunar regolith returned from the Apollo missions range

from 0.1 kPa to 3.1 kPa whereas the same tests on simulant can vary from .1 kPa to 10.3 kPa (Kobaka et al., 2023).

Lunar Highlands Simulant LHS-1 (abbreviated hereafter as LHS) is a mineral-based material developed to approximate the composition and physical characteristics of regolith from the lunar highlands, the lighter color regions on the Moon, visible from Earth. It is composed primarily of plagioclase-rich materials to reflect the anorthosite in highlands regolith. The simulant is engineered by combining multiple terrestrial mineral sources rather than relying on a single rock type. While its particle size distribution is designed to match that of typical Apollo highland soils, it does not contain agglutinates or nanophase iron. Researchers that made geopolymers from lunar simulants (BP-1, JSC-1, LHS-1) found that compressive strength increased after exposure to high temperatures (600 °C) and reduced after exposure to low temperatures (-80 °C) and vacuum. (Mills, et al., 2022).

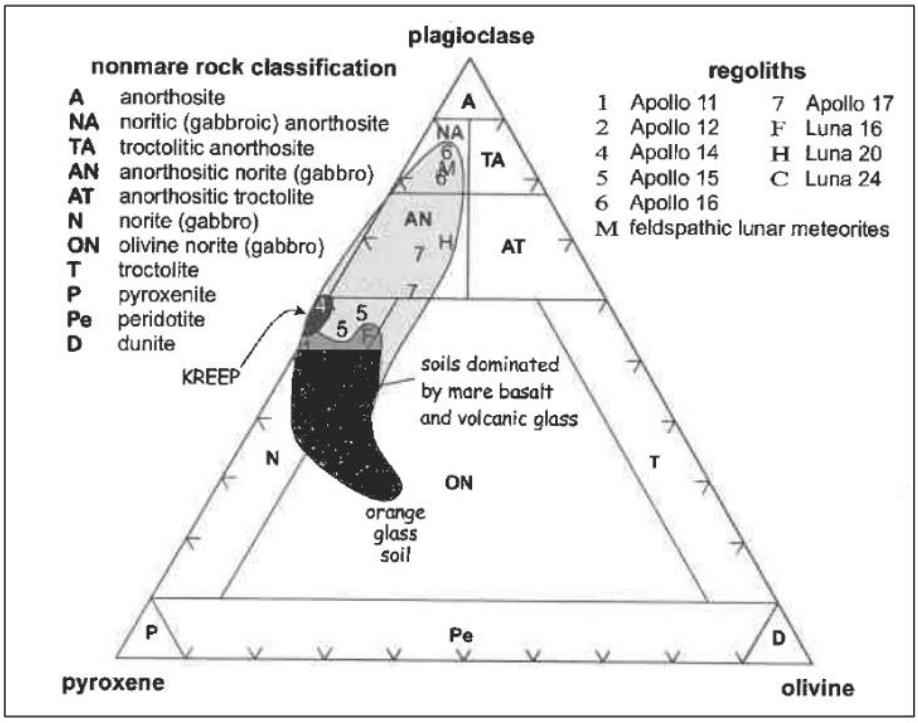

Figure 4: Ternary diagram of the classification of non-mare lunar rocks focusing on the three primary minerals in lunar regolith (Slabic et al., 2024)

The Lunar South Pole is of considerable interest to space agencies with several planning to send spacecraft to the region. The Russian Federation is planning the Luna 25 and Luna 27 missions, the European Space Agency is planning the Lunar Prospecting Rover mission, and NASA is planning to land a crewed mission to the area as part of the Artemis program. In 2023, the Indian Chandrayaan-3 rover, the only successful mission to the lunar south pole, collected data from the surface. There are hundreds of square kilometers where water ice could conceivably exist in the southern polar region and compelling evidence for water ice has been reported by various orbital missions at or near the surface, especially in perpetually shaded craters (Flahaut et al., 2020). Despite this interest and the extensive body of research involving various lunar simulants, studies specifically focused on regolith that mimics the soil of the Lunar South Pole remain limited.

Lunar South Pole regolith simulant, designated LSP-2 by the manufacturer, is referred to

in this thesis as SP2 to distinguish it from LHS. This newly developed SP2 material by the Exolith Lab at the University of Central Florida, was formulated in collaboration with NASA by the private company Space Resource Technologies. At the time of writing in mid-2025, only 7 results could be found on Google scholar regarding this new lunar regolith simulant. SP2 is intended to replicate both the predicted particle size distribution and anorthosite-rich mineralogy of the Moon's South Pole, NASA's primary lunar region of interest. This research material has an increased maximum particle size from 1mm to 2mm, significantly altering the behavior compared to Lunar Highland Simulant. Early sieve analyses of lunar highlands regolith collected during the Apollo Missions that was included for development of LHS excluded particles larger than 1 mm, classifying them instead within the domain of geological studies focused on whole rock specimens. This skewed the results towards smaller particles and SP2 was an effort to try to better reflect particle size distribution estimated to be on the south pole.

SP2 exhibits a median particle size of approximately 106 microns, with 10.74% of its mass comprising particles larger than 1 mm. While the proportion of particles 1-2mm is higher than what was recorded in the Apollo 16 core samples (4.79%), it still falls within the general range anticipated for coarse material commonly present in highland regions of the lunar surface. The development of this regolith simulant used data from the Apollo missions along with mineral composition data from the 2007 Japanese Kagyua orbiter. This mission analyzed the lunar surface and provided some of the first global spectral maps and spectral data of the southern polar region of the Moon (Easter et al., 2024). Data from the 2023 Indian Chandrayaan-3 rover on the lunar south pole, collected after the initial development of the material, was not used to verify SP2 attributes. The bulk chemistry composition, however, is similar to LHS as they both contain the

SiO_2 and Al_2O_3 needed for geopolymerization. Assuming SP2 more accurately represents the lunar south pole, and considering the plans of several nations to target the south pole for future exploration, it is important to begin to generate data for the wider scientific community using this simulant to better understand the environment they might encounter.

2.1.3 Martian regolith

Martian regolith is predominantly basaltic in composition and, due to the planet-wide dust storms, is considered relatively uniform across the surface. There is also local variation due to parent material or exposure to aeolian, volcanic and fluvial erosion as well as frost weathering. The minerology may have different ratios of plagioclase, olivine and pyroxene with minor amounts of magnetite, ilmenite, quartz, potassium feldspars, basaltic glass and salts. Phyllosilicates, or minerals with sheet-like structures are widespread including iron and magnesium smectites which expand when wet. These minerals include illite, chlorite, serpentine and prehnite group minerals found in the areas of the oldest geologic period of Mars, in deposits of the Noachian crust. Sulfates, carbonates and iron oxide are also present in the planetary crust (Fackrell et al., 2021). More detail regarding martian regolith simulant is provided in the raw materials chapter of this thesis.

2.2 Geopolymer concrete[XS2]

2.2.1 Terrestrial geopolymer

Geopolymerization refers to the chemical process by which aluminosilicate materials undergo dissolution in an alkaline environment, breaking down their original structure and subsequently forming a three-dimensional network of polymerized alumina and silica species. Usually, geopolymers are produced by combining alkali activators with industrial by-products.

These include fly ash, which is a residue from coal combustion or slag, which is the waste material from the smelting and refining of metal ore. The resulting geopolymer concrete is an inorganic, molecularly highly cross-linked material synthesized through the alkali activation of silica and alumina-rich precursors. When properly formulated, geopolymer binders exhibit notable advantages over conventional portland cement binder, including superior mechanical strength, enhanced thermal and radiation resistance, efficient water reuse, and improved long-term durability. (Davidovits, 2013)

2.2.2 Extraterrestrial geopolymer

Thankfully for space exploration, the chemical makeup of the regolith found on the Moon and Mars is similar to the industrial byproducts typically used in terrestrial geopolymer. The presence of water has been confirmed in the polar regions of the Moon, which could be used to form aqueous solutions of sodium hydroxide and sodium silicate powders. Water plays a critical role in geopolymer synthesis by facilitating ion transport within the mixture and enabling uniform dispersion and activation of the precursor materials. (Zhou et al., 2020). The use of lunar simulant to make geopolymer has been well documented (Zuo et al., 2022; Lin et al., 1992; Davis et al., 2017; Debbarma et al., 2024). Given its high silica and alumina content (Montes, 2015), lunar regolith presents a viable feedstock for producing geopolymer binders, supporting the potential for in-situ construction on the Moon. The usage of regolith which is ubiquitous on the lunar and martian surface, along with the possible reclamation of mixing water after curing (Lee et al., 2022) make geopolymer concrete particularly well-suited for in-situ resource utilization on the Moon and Mars where the presence of water is not certain in any given location.

Results that are optimized for regolith simulant may not be ideal for actual regolith but martian geopolymer is also possible. The chemical makeup of martian regolith has been shown to be conducive to geopolymerization, though with less precursors and more alkali activator, so simulants are appropriate for the experiment. Researchers from the University of Delaware were able to successfully make geopolymer with Martian regolith simulant (MGS-1C) but had to increase the aluminosilicate content and decrease the proportion of solids in the slurry to activate the simulant. MGS-1C is a clay-enriched variant of the Martian regolith simulant MGS-1, with a higher proportion of fine particles to improve its binding performance. In this study that compared various simulants for geopolymer development, all samples were sieved to 75 μm (Koboka, et al., 2023).

The iron and magnesium content was thought to contribute to the reduction of compressive strength (Mills et al., 2022). This underscores the need for reinforcement in concrete especially on Mars. Thankfully, the presence of iron meteorites has been documented by several missions to the red planet, so the production of reinforcement bar, or rebar is also possible. When researchers from the University of Birmingham subjected JSC MARS-1A regolith simulant to geopolymerization, they found that extra milling was required to reduce the particle size, but after curing it was close in compressive and flexural strength to common building bricks (3.5 MPa). Researchers have found lunar regolith geopolymer concrete to be stronger than martian regolith simulant concrete, but despite this discrepancy, it is still a suitable building material for future settlement (Alexiadis et al., 2017)

2.2.3 Challenges of extraterrestrial construction materials

Attributes of actual regolith, such as particle size distribution, chemical composition, or environmental history, may differ substantially from those of commercially available simulants regarding processing geopolymer. There is significant variation based on the extraction location depending on several factors, especially the age of the parent material. Refining concrete elsewhere may parallel the challenges on Earth, where soil cannot simply be collected from any random location and used directly for concrete production. When humans can interact with the varieties of actual regolith not yet known to science on the Moon and Mars, we are likely to rethink how we formulate simulants in response to new data.

In addition, the conditions on the Moon are unlikely to remain static as humans develop the lunar surface for settlement. Sensor data attained on the Apollo missions confirmed the presence of tremors. Thermal expansion and contraction of the lunar module, driven by extreme temperature fluctuations between lunar day and night, produced vibrations detectable by seismometers. This indicates the Moon's surface is highly sensitive to seismic disturbances, as instruments were able to register the slight movement of the module scratching the lunar surface from over 100 meters away. (Civilini , 2023; Cadena et al., 2020). As humans begin to live and work on Earth's natural satellite, it is inevitable that vibrations will become more frequent and intense. Designing infrastructure that can withstand these moonquakes is complicated by the limited knowledge of the contributing geophysical processes. This underscores the need to develop robust building materials, as structures must be designed not only to withstand the current conditions of the Moon but possibly more challenging conditions in the future.

2.2.3.1 Low gravity[XS3]

Researchers at Pennsylvania State University found that tri-calcium silicate cement cured in microgravity on the International Space Station had considerably lower strength because of the large pores that developed. Without the directional force of gravity to allow constituents of different densities to settle, air bubbles remained in the sample. (Moraes Neves et al., 2019) Because this cement cured in a microgravity environment is more porous, one might assume that geopolymer concrete cured in the lower gravity environment of the Moon and Mars might also be more porous. Concrete has been cured in a centrifuge on the International Space Station to simulate the gravity of the Moon and Mars, but those results have not yet been published as of 2025 (Müller et al., 2023). To date, no studies have been published on concrete cured in vacuum conditions using centrifugation to determine whether the cohesion achieved under gravitational curing can be applied or improved in a vacuum environment. (Zuo et al., 2022). If one were to design a concrete mixer that could function on the Moon or Mars, the evidence in this literature suggests that a pressurized centrifuge might be a plausible method of producing concrete bricks.

2.2.3.2 Concrete cured in a vacuum

Researchers found sulfur concrete cured in a vacuum to have poor micromorphology and large pores with less bonding between particles (Zuo et al., 2022). Researchers in Louisiana Tech University attempted to cure samples of lunar regolith simulant geopolymer concrete and were unable to attain any measurable compressive strength from the samples that cured longest in a vacuum. Because these samples were small (less than a few cubic centimeters), researchers used linear regression analysis to estimate that 3.42 MPa would be the average compressive strength if the samples were larger. The minimum compressive strength for concrete according to U.S.

Marine Corps Standards is 25-30 MPa. Even when accounting for the Moon's one-sixth gravity and assuming a directly proportional reduction in required compressive strength, the target range of 4–6 MPa remains unmet for concrete cured in a vacuum. The evidence in this literature suggests that for concrete to cure properly with the necessary compressive strength, for use on the Moon and Mars, it must be cured with some air pressure. It is worth mentioning that while air pressure on the Moon ranges from 9.869×10^{-15} to 9.869×10^{-12} atm, the air pressure reached for the experiment by (Davis et al. 2017) was several orders of magnitude higher at 1.974×10^{-6}, underscoring the need for air pressure when curing concrete.

2.2.4 Mixture design factors

The liquid-to-solid ratio, defined as the mass ratio of alkaline activator solution to regolith simulant, plays a critical role in governing both the workability and the chemical reactivity of geopolymer mixtures. At high liquid-to-solid ratios, the mixture forms a highly fluid, low-viscosity slurry, while moderate ratios yield a workable paste suitable for extrusion or casting. In contrast, low liquid-to-solid ratios produce a stiff, minimally wetted mixture with limited flowability. For effective geopolymerization, the liquid-to-solid ratio must be sufficiently high to enable the alkaline solution—typically comprising sodium hydroxide, sodium silicate, and additional silica—to dissolve aluminosilicate species from the simulant surface. However, excessive dilution can reduce the concentration of reactive alumina, which is necessary for cross-linking with soluble silicates. An optimal balance is therefore essential to ensure efficient dissolution, gel formation, and mechanical performance.

$$Silica\ Modulus\left(M_s\right)=\frac{Mass\ of\ SiO_2}{Mass\ of\ Na_2O}$$

Equation 1: Silica Modulus

Another key parameter is the silica modulus, as shown in Equation 1, which is defined as the mass ratio of silicon dioxide (SiO_2) to sodium oxide (Na_2O) in the activator solution. Sodium hydroxide acts as a strong base, initiating dissolution of the aluminosilicate framework in the regolith. As alumina is liberated, a gel begins to form through initial ionic interactions, which are later stabilized by covalent bonding with reactive silica, producing a silicon–oxygen–aluminum (Si–O–Al) network. When the silica modulus is too low, indicating excess sodium hydroxide, the mixture may exhibit rapid setting, brittleness, and increased efflorescence due to unreacted alkalis. Conversely, if the silica modulus is too high, the resulting drop in pH can slow dissolution kinetics and leave excess silica unincorporated due to insufficient dissolved alumina. Dawood et al. (2024) demonstrated that increasing silica modulus can significantly delay setting times, limiting practical application despite theoretical reactivity. Their study, like ours, did not find a strong correlation between silica modulus and compressive strength at high values, attributing this to an imbalance between available silica and the alumina required for effective network formation. Additionally, the research supported the observation that lower liquid-to-solid ratios generally yield higher compressive strengths, reinforcing the need for careful optimization of both parameters in lunar or martian geopolymer formulation.

Another factor that may affect the compressive strength and curing time is the curing temperature. In one study, though various factors were tested to determine the highest compressive strength of lunar geopolymer, the sample with the highest compression strength was 70°C

(Dawood et al., 2024). The energy needed to maintain an oven to heat bricks on the Moon or Mars would be considerable. Winter temperatures at the martian poles can reach as low as –133 °C, while permanently shadowed craters near the south pole of the Moon have been recorded at temperatures as low as –230 °C. (Jones, 2009). Therefore, one might rightfully question the feasibility of maintaining an oven on the Moon or Mars to cure bricks at, for example 70°C, in such a frigid environment. If the intention of space agencies is to construct settlements on the Moon and Mars for long term settlement, the cost-saving prospect of manufacturing building materials from in-situ resources instead of hauling cement from Earth would easily justify the expenditure. Concerning the viability of human settlement off world, oxygen is a far more urgent need than concrete, and to address this, NASA is considering proposals ("Nasa Kennedy," 2019; Sibille et al., 2009) to extract oxygen from molten regolith at temperatures of 1600°C. The need for a 70°C oven seems trite in comparison.

Bondar et al. (2011) also researched proportions and types of alkali activators, focusing on terrestrial geopolymers. Based on their findings, sodium hydroxide (NaOH) dissolved minerals more quickly than KOH and was more cost effective, for these reasons, 10 molar NaOH was chosen for this thesis. Geopolymers were cured at 60°C and 40°C, and of the two, the samples cured at 60°C had higher compressive strengths. The alkalinity of NaOH, in conjunction with silica, SiO_2 and sodium silicate, also known as water glass (Na_2O+SiO_2) allowed thorough geopolymerization of natural pozzolans in their study. Sodium silicate is typically granular, in powder form or in a solution. To aid the dissolution of the siliceous and aluminous materials, the solutions used had a pH of 12-14 in their experiments. (Bondar et al., 2011)

2.2.5 Centrifugation of geopolymer

Li et al. (2024) were able to significantly improve the strength and reduce the porosity of alkali activated slag (AAS) paste through centrifugation in test tubes. As one can see from the SEM images in Figure 5, the gel products became increasingly smooth and cohesive with more centrifugation. The compressive strength of samples not centrifuged was 30.7 MPa. When centrifuged at 1000, 3000 and 5000 r/min, the strength improved to 40.1, 66.7 and 71.8 MPa, respectively. The cumulative pore volumes of AAS pastes decreased to 0.098 mL/g, 0.076 mL/g, and 0.065 mL/g when centrifuged at 1000, 3000, and 5000 r/min, respectively. Compared to pastes without centrifugation, these reductions amount to roughly 10%, 30%, and 40%.

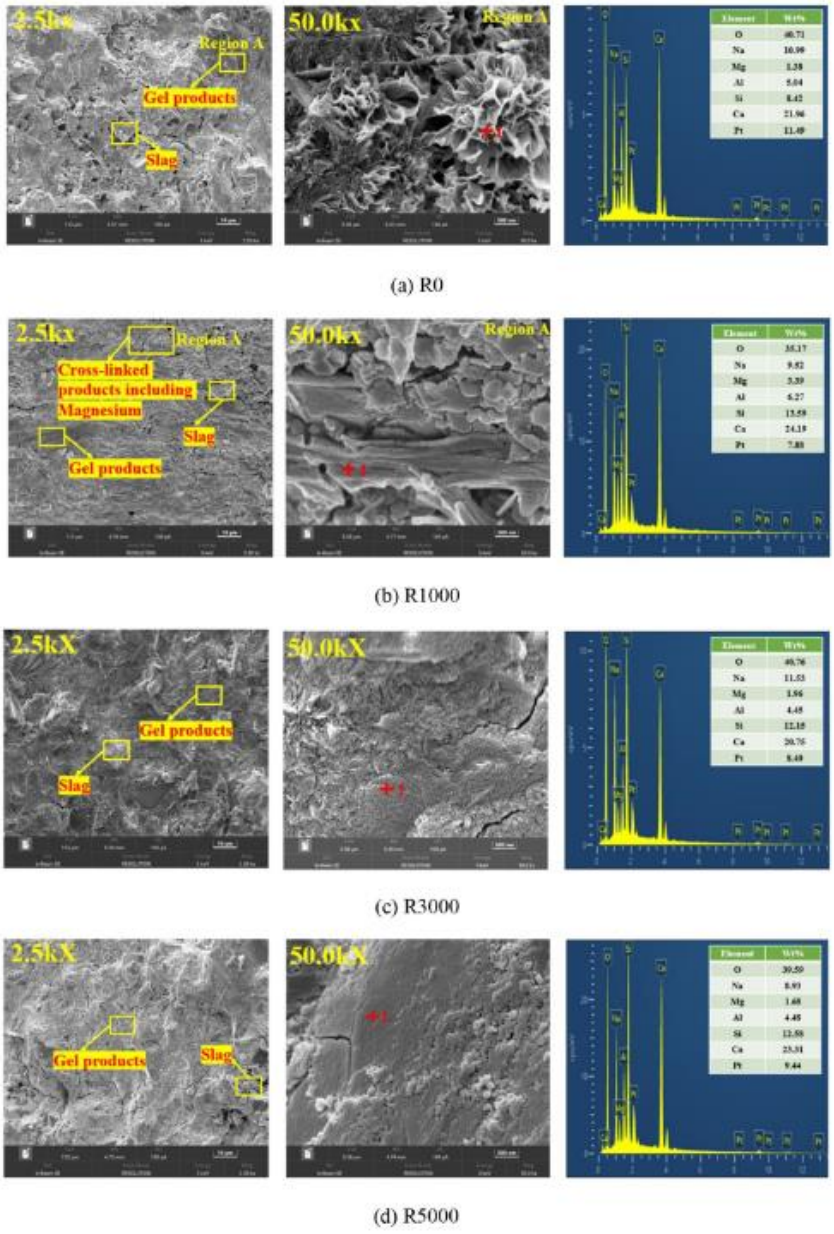

Figure 5: SEM images of Alkali Activated Slag revolved at different speeds (a) Control sample R0 (b) R1000, 1000 Rotations Per Minute (c) R3000, 3000 RPM (d) R5000, 5000 RPM

The Transmission Electron Microscope (TEM) results in Figure 6 show that as the centrifugal rate increases, the morphology becomes less flaky and disjointed. Control samples that were not subjected to centrifugation developed flower cluster gels in a loose matrix with a higher percentage of unreacted slag. As samples were subjected to centrifugation, by layered strip gels

indicated more crosslinking and better geopolymerization. At 5000 rpm centrifugation, samples had denser, more cohesive and rounded globule gels.

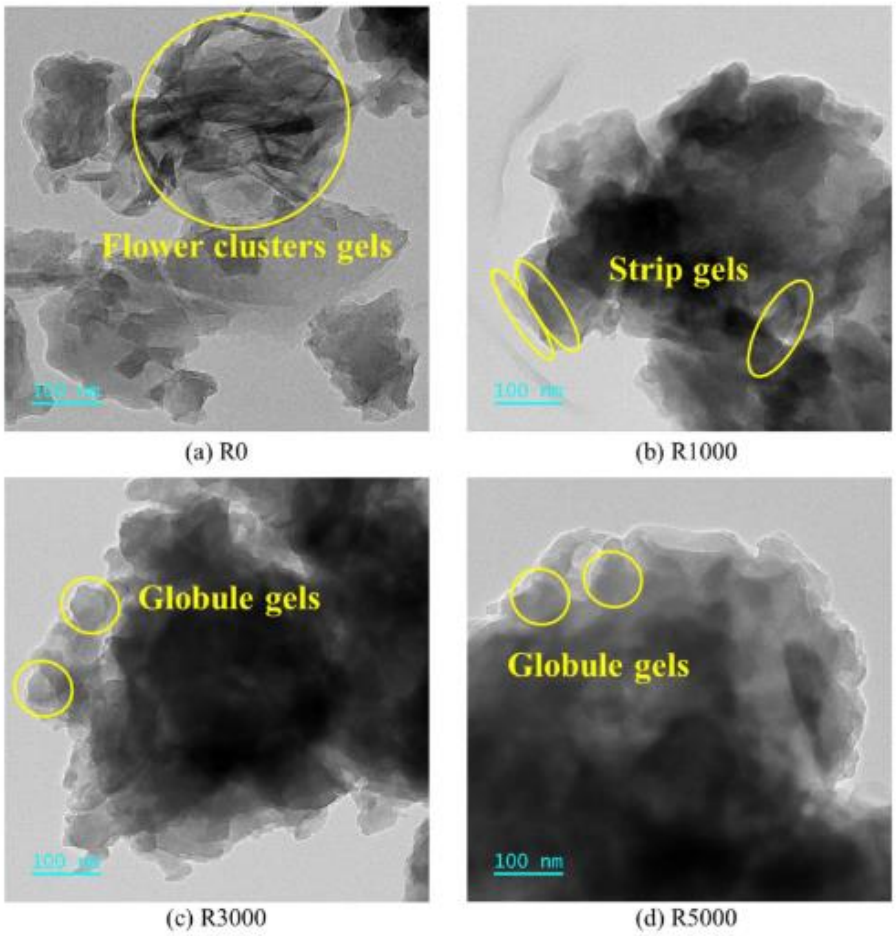

Figure 6: TEM images of AAS cured with (a) no centrifugation (b) 1000 RPM (c) 3000 RPM (d) 5000 RPM

Pan et al (2022) was able to attain similar results by increasing compressive strength through centrifugation. Geopolymer samples revolved at 1000 rpm were able to reach a compressive strength of 45.3 MPa, which was a 70% strength increase compared to samples not revolved in a centrifuge. These samples, however, were attained by mixing geopolymer made from products of industrial waste, not regolith simulant, and using a medical centrifuge with test tubes,

not a machine designed to make a usable product. A porous and weakly bonded interfacial transition zone (ITZ) can develop between the fine particle binder and the coarse aggregate when all fine particles are flung to one side by centrifugal force. Without fine material to fill the spaces between coarse particles, this deficient microstructure ultimately leads to reduced compressive strength (Demie et al., 2013). Therefore, in concrete that has a wider particle size distribution and is not homogeneous like the above study, an RPM of 5000 would not be optimum as an ITZ cannot develop without coarse and fine particles intermingling.

3 PROBLEM STATEMENT AND OBJECTIVES

If the first inhabitants of the Moon and Mars are to make concrete, it would be pragmatic for them to make concrete out of the most abundant resource around them, regolith. If those inhabitants are then going to make concrete bricks to build, it would also be pragmatic for them to make those bricks stronger, possibly through better mixture design and centrifugation. Therefore, if they make centrifuged bricks or tiles, it would be useful for them to have a machine that could make several simultaneously. This thesis aims to help bring these possibilities closer to fruition. The goal of this work is to advance the development of lunar and martian geopolymer concrete through demonstrating the effects of mixture design and curing factors on compressive strength. In addition, this thesis attempts to test these principles in conjunction with conducting compressive strength tests of centrifuged lunar and martian concrete. Additionally, this thesis prototypes the core element of a machine designed to produce geopolymer tiles in a low-gravity environment. Ultimately, this study aims to advance the concept of centrifugally cured geopolymer from theoretical laboratory research toward the practical manufacture of a functional product.

On the ISS, when tri-calcium silicate, the principal reactive compound of ordinary portland cement, was cured in a microgravity environment, there was a 20% increase in porosity of the sample due to a lack of buoyancy to force the air bubbles to exit the slurry before curing (Moraes Neves et al., 2019). While partial gravity on the Moon and Mars offers some advantage over microgravity conditions like those on the ISS, the requirement for high-strength concrete persists. Under such conditions, slurry viscosity impedes the escape of air bubbles, whose buoyancy is significantly diminished. The resulting porosity as the mix solidifies would therefore still weaken the strength of the concrete. A concentrated load on a concrete sample near a subsurface void may

trigger fracture propagation and compromise performance. In addition, if the number of problematic air voids close to the surface of the concrete is not reduced before the mix is fully cured in a pressurized air containment, these air pockets could rupture when exposed to the vacuum of space because of the differential pressure. Moreover, the potential for increasingly severe moonquakes and marsquakes, driven by human activity such as launches and landings, as well as meteorite impacts, heightens the risk of fractures that could expose and rupture subsurface air pockets. A small leak of a pressurized containment exposed to a vacuum could lead to a catastrophic failure putting lives at risk for any that may be inside. Collectively, these scenarios highlight the importance of minimizing porosity in low-gravity-cured concrete, to ensure the structural reliability essential for human safety.

3.1 Research significance

This thesis attempts to further the understanding of centrifuged geopolymer made from regolith stimulant by independently verifying the results for different applications of the following main studies. Bondar et al. (2011) investigated the factors that could contribute to compressive strength of natural pozzolans including silica modulus, liquid/solid ratio, along with the type and strength of alkaline reagents. By building on work from this study and using regolith simulant instead of natural pozzolans, this thesis aims to apply this progress of producing geopolymer concrete towards extraterrestrial settlement.

Dawood et al (2024), further developed the understanding of the importance of silica modulus, liquid-to-solid ratio, and included temperature in testing the microstructure and micromechanical properties of lunar regolith simulant geopolymer with nanoindentation. While the microstructure and bulk properties of extraterrestrial simulant geopolymers have been

previously studied, this research aims to further investigate how the combination of silica modulus and liquid-to-solid ratio relates to compressive strength and slurry behavior regarding printability. Therefore, a preliminary analysis aims to increase understanding of the bulk properties of these materials by varying liquid-to-solid ratios and silica moduli. In addition to investigating one type of lunar simulant, in this thesis, lunar highlands simulant, lunar south polar simulant and Mars global simulant with hydrated clay are all tested.

Li et al. (2024) were able to prove an increase in compressive strength of terrestrial geopolymer with centrifugation. However, extraterrestrial regolith simulant geopolymer has not been centrifuged and tested to confirm an increase in compressive strength. To date, no ASTM-standard compressive strength tests using 5 cm concrete cubes have previously been performed on centrifuged specimens to verify potential changes in bulk properties of extra-terrestrial geopolymer. All of these new ideas are put to the test in this thesis.

3.2 Objectives

The objective of this thesis is to evaluate whether centrifugation of geopolymer made from extraterrestrial regolith simulants can enhance compressive strength, and to explore the mechanical implications and potential directions for further investigation based on the findings. Based on this rationale, the following steps were carried out: 1. Execute a preliminary investigation of the effect of mix design parameters on extraterrestrial simulant geopolymer workability and compressive strength. 2. Compare the compressive strength of centrifuged geopolymer specimens cured at different times to corresponding control samples. 3. Provide insight into the design an extraterrestrial geopolymer mixer and centrifuge prototype

4 MATERIALS, MIX DESIGN AND TESTING METHODOLOGIES

4.1 Raw materials

The three extraterrestrial simulants, LHS, SP2, and MGS-1C are each unique regarding appearance, particle size, behavior and composition as it relates to geopolymerization. As one can see in Figure 7, SP2 has a light colored, fluffy texture with moderate cohesion, LHS is a fine, pale gray, slightly cohesive powder and MGS-1C is a light pinkish brown with high cohesion. LHS and SP2 are both general purpose simulants, so are more likely to replicate the regolith as it can be found on the lunar surface. The manufacturer specifications of MGS-1C indicate ISRU applications, so this simulant is better suited for printability as the product was designed for this purpose.

Figure 7: (a) LHS-1 Simulant (b) LSP-2 Simulant (c) MGS-1C Simulant (Space Resource Technologies, 2023)

In Table 1, the density, median and range of the three simulants are shown. A useful way to visualize the particle size characteristics of these simulants is by comparing them to the particle size classifications established by the U.S. Department of Agriculture. (USDA, 2022). SP2 has the widest range from clay to fine gravel with 0.04µm-2.0mm. MGS-1C has the smallest range with fine silt to very coarse sand at 0.4µm-1.0mm, and LHS is in between the two with clay to very

coarse sand at 0.04µm-1.0 mm. With the median particle size, SP2 has the largest with 1.067mm, MGS-1C has the smallest with 0.014mm, and LHS is in between the two with 0.051mm.

Simulant Name	**Uncompressed Bulk Density (g/cm^3)**	**Median Particle Size, D50 (µm)**	**Particle Size Range (µm)**
LSP-2 Lunar South Pole Simulant	1.45	106	<0.04 – 2000
LHS-1 Highlands Simulant	1.27	51	<0.04 – 1000
MGS-1C Mars Global Hydrated Clay Simulant	1.12	14	<0.4 – 1000

Table 1: Bulk properties of (a) LHS-1 Simulant (b) LSP-2 Simulant (c) MGS-1C Simulant (Space Resource Technologies, 2023)

Figure 8 presents the overlayed cumulative particle size distribution curves for both LHS-1 and MGS-1C, which are used interchangeably to in the text of this thesis as LHS and MGS. The steep slope of the LHS curve indicates a narrower particle size distribution, whereas the more gradual slope of the MGS-1C curve reflects a broader distribution of quantities of particle sizes within the range.

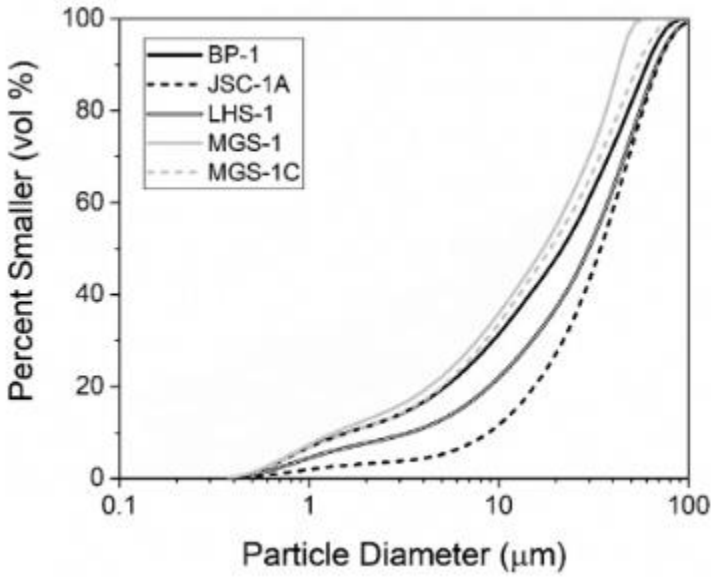

Figure 8: The cumulative particle size distribution of the simulants was determined through laser diffraction analysis, expressed in terms of differential volume percentage, following initial dry sieving using a No. 200 mesh (75 μm) screen. (Mills et al., 2021)

The particle size of these two simulants is further investigated (Long-Fox et al., 2023) with Figure 9 where the density function is depicted with a red line. With LHS, the strong unimodal peak around 0.07-0.09 mm indicates more uniform particle sizes which is favorable to dense packing and better strength in geopolymerization. With MGS, the multimodal distribution with peaks around 0.02, 0.01 and 0.1 mm indicates the presence of both fine particles, coarser grains and a substantial fraction of intermediate sizes.

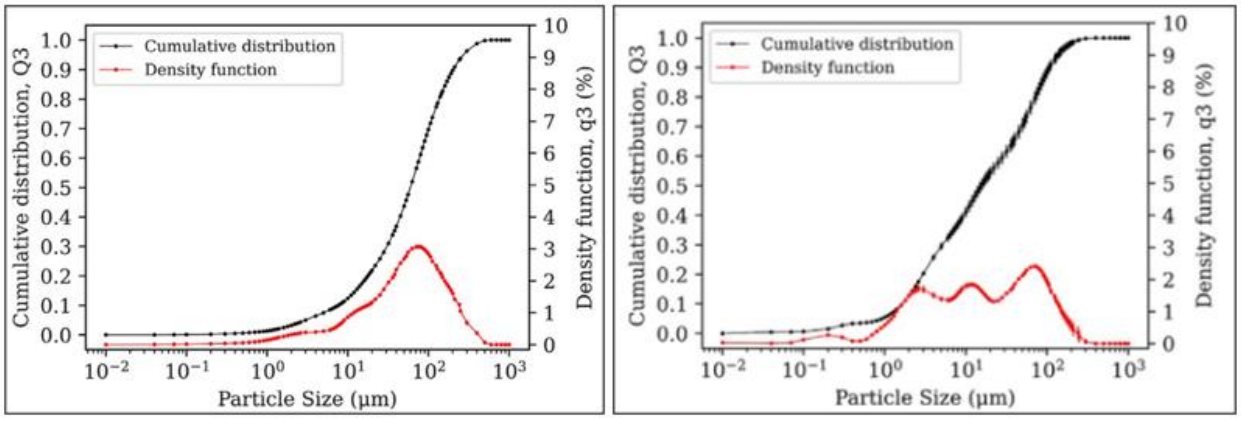

Figure 9: Particle size distribution plots of LHS-1 (left) and MGS-1C (right) (Long-Fox et al., 2023)

These differences suggest that the two simulants exhibit distinct flowability and printability characteristics during processing as well as different compressive strengths. LHS has very fine particles that have greater surface area for alkali activation, supporting denser and stronger matrices. With more uniformity in particle sizes, LHS can pack more tightly, reducing voids and porosity. MGS also has fine sized particles and supports rapid reaction but with a wider range of particle sizes is less likely to pack densely. The abundance of clay sized particles in MGS allow for greater absorption of water, increasing viscosity and reducing flow, which is a challenge for pouring the material but is ideal for printability. As seen in Figure 10 (Easter et al., 2024), SP2 has coarser particles that may slow dissolution and reaction kinetics but closely mimic Apollo 60009 core soil. The wider distribution of LSP-2 (which is referred in this thesis as SP2) which includes coarser particles make it ideal for simulating construction scenarios at the lunar south pole but may reduce strength unless processed further. MGS-1C, with its clay-like fineness, enhances geopolymerization potential but may lead to shrinkage and higher water demand. LHS offers a balance between the flowability of SP2 and the printability of MGS.

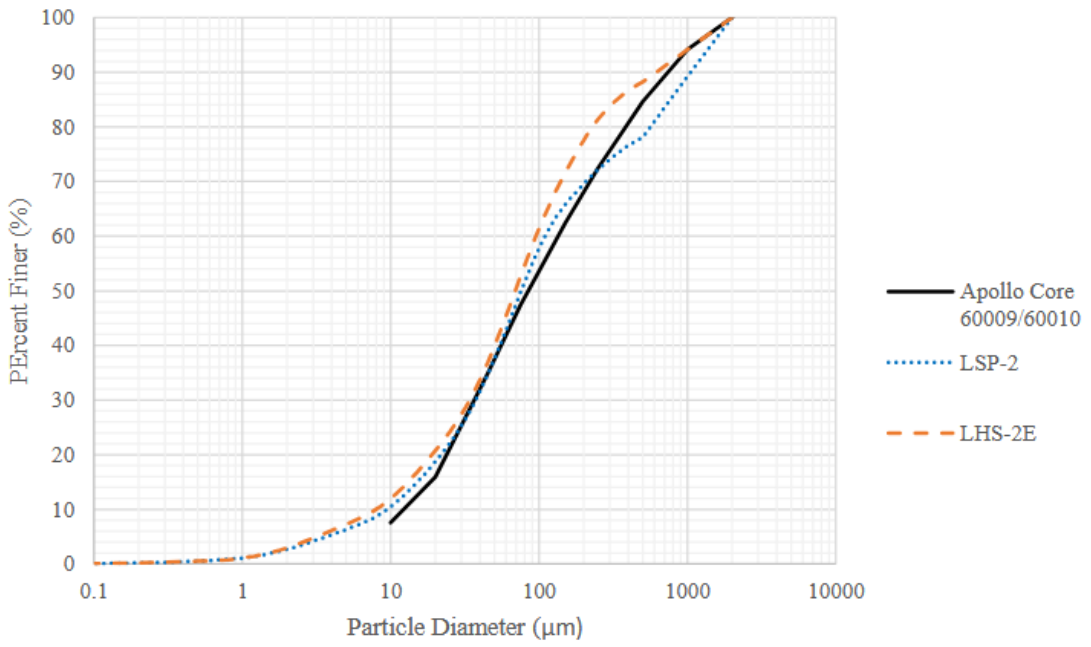

Figure 10: Particle Size Distribution curve of LSP-2 compared to the Apollo 60009/60010 sieved below 2mm (Easter et al., 2024)

As can be seen in Table 2, all three regolith simulants have high levels of alumina and silica which contribute to the geopolymer network. The two lunar simulants have high alumina which is crucial for cross-linking aluminosilicate bonds. The Mars simulant however is deficient in this regard which contributes to lower strength. The lower proportion of calcium, at 13-17% for all three has the disadvantage of a slow reaction rate and a contributing factor to low mechanical properties (Zheng, et al., 2024) compared to lunar simulant geopolymer with additives and 20% calcium, which can reach as high as 100 MPa (Shao et al. 2024). The presence of the native alkalis of Na_2O and K_2O from 3-5% in the lunar simulants lower the need for activators when chemically liberated, but the higher presence of 7.4% in MGS may over contribute, leading to instability and cracking. The high presence of iron and magnesium in MGS, 12% and 10%, could interfere with geopolymer gel chemistry. As they are excluded from the geopolymer chemical reaction, these

particles have weaker bonds which may lead to durability issues. The results of this thesis correspond with these mineralogy insights, with MGS geopolymer having lower strength than LHS.

Table 2 Composition of Lunar and Martian Regolith Simulants (Space Resource Technologies, 2023,2024)

Composition (%)		**LHS-1**	**LSP-2**	**MGS-1C**
Mineralogy	Anorthosite	74.4	90	16.4
	Glass-rich Basalt	24.7	10	13.7
	Ilmenite	0.4		
	Bronzite	0.3		
	Olivine	0.2		8.2
	Smectite			40
	Pyroxene			12.2
	Mg-sulfate			2.4
	Ferrihydrite			2.1
	Hydrated silica			1.8
	Magnetite			1.1
	Anhydrite			1
	Fe-carbonate			0.8
	Hematite			0.3
Bulk Chemistry (Oxide)	SiO2	49.12	47.13	44.8
	TiO2	0.63	0.16	0.4
	Al2O3	26.29	27.96	9.8
	FeO	3.2	1.24	
	Fe2O3			12
	MnO	0.06	0.02	0.1
	MgO	2.86	0.71	9.9
	CaO	13.52	17.5	15.3
	Na2O	2.55	4.02	
	K2O	0.34	0.42	3.4
	P2O5	0.17	0.83	1
	LOI	0.41		
	SO3			2.3
	Cl			0.5
	Cr2O3			0.1
	NiO			0.1
	SrO			0.2

4.2 Mix design

To convert regolith simulant into geopolymer concrete, the simulant was mixed with sodium hydroxide and silica sources in calculated proportions. The efficiency of the geopolymerization reaction is primarily governed by two parameters: the liquid-to-solid (L/S) ratio and the silica modulus (SiO_2/Na_2O). To investigate their influence, L/S ratios ranging from 0.2 to 0.4 were selected for both SP2 and LHS simulants, based on preliminary trials that indicated these ranges were most likely to yield viable and consistent results. In each mixture, the solid component had a fixed mass of regolith simulant, while the liquid component served as the alkaline activator. Within each L/S ratio, silica moduli of 1.0, 1.5, and 2.0 were implemented to assess their effect on material behavior.

The activator solution was prepared by combining sodium hydroxide and sodium silicate in appropriate proportions to achieve the desired silica modulus, with the addition of silica dioxide powders. A highly alkaline environment was necessary to dissolve aluminosilicate phases in the simulant, so a 10 M sodium hydroxide solution (pH ~14) was used. This base was prepared by dissolving 400 g of NaOH powder into 1 liter of distilled water, yielding a solution with approximately 60% water by mass. To prepare a silica modulus of 1, a 1:1 mass ratio of sodium silicate to sodium hydroxide was used. For higher moduli of 1.5 and 2.0, the proportions were changed accordingly thereby increasing the relative silica content. Additional silica dioxide powder was added to achieve the specific silica modulus. Sodium silicate (Na_2SiO_3), also known as water glass, served as the primary source of silica. Because commercial sodium silicate contains approximately 60% water, only the solid content was included in the modulus calculations. The required quantity of additional SiO_2 was determined by subtracting the silica already present in the

sodium silicate solution from the total target silica content. This difference was used to calculate the amount of SiO_2 needed to achieve the desired silica modulus in the activator solution. The masses of all reagents to this mixture are listed Table 12 in the appendix.

4.3 Experimentation and methodology

First, the proportions of all needed materials were calculated, weighed and verified by the lab participants. As depicted in Figure 11, a magnetic stir bar in a beaker with the proper amount of sodium hydroxide was zeroed on a scale. Because water glass is a viscous and adhesive substance, it was added from a secondary container and weighed as it was combined with the sodium hydroxide. The beakers were then transferred to a magnetic stirrer and reagents were mixed while added. The previously weighed silica was then added and mixed until homogenous, with no silica powder remaining on the bottom of the beaker. While the alkali activator was still completely liquid, it was transferred to a polymer cup containing the appropriate mass of regolith simulant. Using a cordless handheld drill with a paint mixer attachment, the regolith and alkali activator were mixed until homogeneous. The specifications on the drill are listed as 600 rotations per minute, but considerable friction from the dense mixture often prevented the implementation of the highest setting.

Figure 11: Steps of geopolymer processing. 1) Mixing sodium hydroxide with sodium silicate, 2) Mixing silica with the liquid mixture, 3)Mixing alkali activator with simulant until homogenous , 4) Pouring and placement wet concrete samples in the oven

The resulting slurry was then poured in ASTM C109 standard 5 cm cubic molds and immediately placed in the oven. The molds were additively manufactured with Acrylonitrile Butadiene Styrene (ABS) polymer filament in a Bambu X1C 3-D printer. After the elapsed time in curing in a dehumidified oven at 70°C for their elapsed time the samples were removed and cooled before the compressive strength test. This process was repeated for all experiments. Compressive strength test took place in a Controls Model 50-C78Z00 compression testing machine like what is shown in Figure 12. All samples were subjected to an ASTM standard C109 compressive strength test at a rate of 1.38 MPa/s.

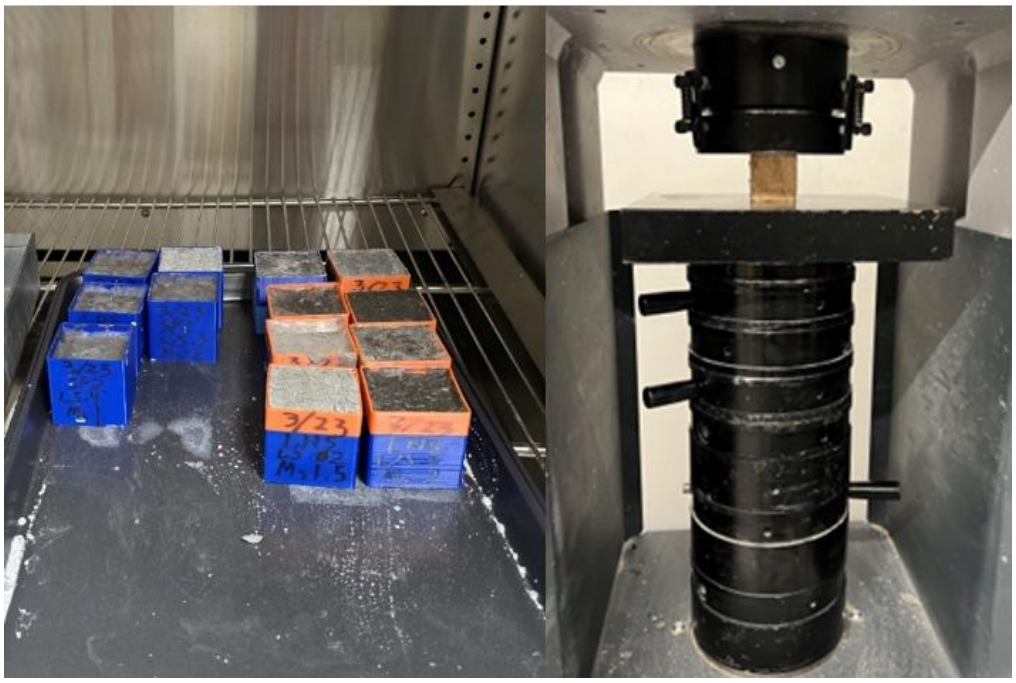

Figure 12: A variety of curing geopolymer samples in the oven (left) A compressive strength test (right)

Upon further investigation, to better understand the microstructure of samples, some were then subjected to analysis in a JEOL 6010 scanning electron microscope (SEM) like what is shown in Figure 13.

Figure 13: The author placing samples in a Scanning Electron Microscope

With the preparation methodology established, subsequent experimental tasks were undertaken to enhance understanding of the formulation and behavior of extraterrestrial simulant-based geopolymers. The optimal liquid-to-solid ratio and silica modulus were identified for the most suitable regolith simulant through evaluation of compressive strength, flowability, and rheological characteristics in the preliminary bulk property analysis. Based on these findings, the most effective proportions of regolith simulant, sodium hydroxide, and silicon dioxide were selected. Cubic samples of the resulting slurry were then prepared, subjected to centrifugation using a modified mixing apparatus, and tested for compressive strength. Variability in regolith simulant received from the manufacturer warranted additional analysis. Post-experimental characterization was conducted using SEM to evaluate microstructural features. Additionally, geopolymer tiles were fabricated using a custom mixer-blade centrifuge chamber developed by

the author in collaboration with Dylan Depew, an undergraduate in mechanical engineering at Texas State University. This apparatus served as the focal component of the Texas State University submission to the NASA MINDS competition in both 2024 and 2025. The centrifuge chamber was fastened to a multi-speed drill press to verify functionality. Throughout these processes, potential workability, printability, compressive strength, centrifugation feasibility, and potential improvements to the mixing system prototype were investigated.

4.3.1 Preliminary bulk property analysis

To establish suitable proportions of regolith simulant, sodium hydroxide, and silica for centrifugation, preliminary trials were conducted. These experiments aimed to evaluate the effects of varying liquid-to-solid ratios and silica moduli on the workability and compressive strength of the resulting geopolymer mixtures. A series of formulations incorporating different combinations of regolith simulant, sodium hydroxide, sodium silicate, and silicon dioxide (see Table 12) were systematically prepared, cured, and subjected to compressive strength tests. Each sample was cured in an oven at 70°C for 14 days under identical conditions. It was observed that premature demolding led to fragile edges prone to damage, which compromised the integrity and uniformity of the specimens. Therefore, to minimize variability and ensure reliable compressive strength data, all LHS, SP2, and MGS samples were kept in their molds for the full 14-day curing period, then demolded and tested after cooling to room temperature.

4.3.2 Centrifugation

To determine the optimal time interval between casting and centrifugation, the compressive strengths of centrifuged specimens were compared to those of control samples cured under

identical conditions without centrifugation at various curing stages. The centrifugation speed must be high enough to reduce porosity yet carefully controlled to prevent excessive particle segregation. Because literature (Li et al., 2024) indicated an increase in strength directly proportional to centrifugation speed, the decision was made to exceed Earth gravity, but not to 5000 RPM as some studies executed. If all coarse particles concentrate on the periphery and all fine particles concentrate toward the axis, the concrete will not be properly mixed. A degree of particle segregation can be advantageous, to make the outward facing side of the tile stronger with a higher percentage of herd aggregate, more tightly compacted and resistant to cracks. This particle separation, inevitable in centrifugation must not occur to such an excessive degree to jeopardize the strength of the mix, and fundamental functionality of the concrete. In properly mixed concrete, fine particles surround and chemically bond to aggregate. Therefore, the best centrifugal speed for striking this balance must be determined by rigorous in-situ experimentation. The slurry must also be allowed to cure for an appropriate period of time before centrifugation as particles will move less freely if the mix is more viscous.

To test these principles, four pairs of samples were cast into 5 cm cubic molds made from additively manufactured ABS filament. In all samples tested, the liquid/solid ratio was 0.3 and the silica modulus is 1 as this combination had an appropriate balance between workability and compressive strength. The samples were prepared and poured at time intervals of 170, 140, 100, and 60 minutes prior to centrifugation. The samples designated for centrifugation were placed in the custom-designed cube centrifuge adapter, which was mounted on a drill press. A rendering of the additively manufactured adapter is shown in Figure 14.

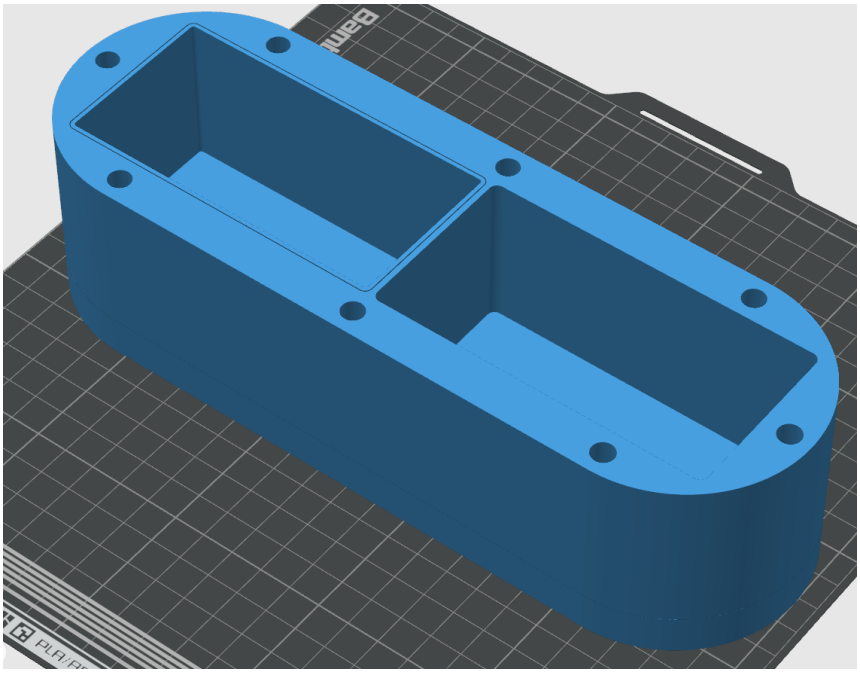

Figure 14: Compression test cube centrifuge drill press adapter, additive manufacturing rendering

Half of these eight samples were centrifuged for 3 hours at 480 RPM, 25.4 cm from the center, each undergoing 13.9 Gs, or gravitational force equivalent units. The execution of this experiment can be seen in Figure 15.

Figure 15: Compression cube centrifuge drill press adapter, closeup and in operation

The samples were then heated to 70°C that same day, demolded 4 days later and heated for an additional 10 days. The samples before demolding can be seen in Figure 16. After being removed from the oven and cooling to room temperature, all 8 samples were subjected to an ASTM Standard C109 compressive strength test. The results were analyzed and the centrifuged sample with the optimum strength and failure behavior was compared in porosity and microstructure to its corresponding control with a JEOL Scanning Electron Microscope.

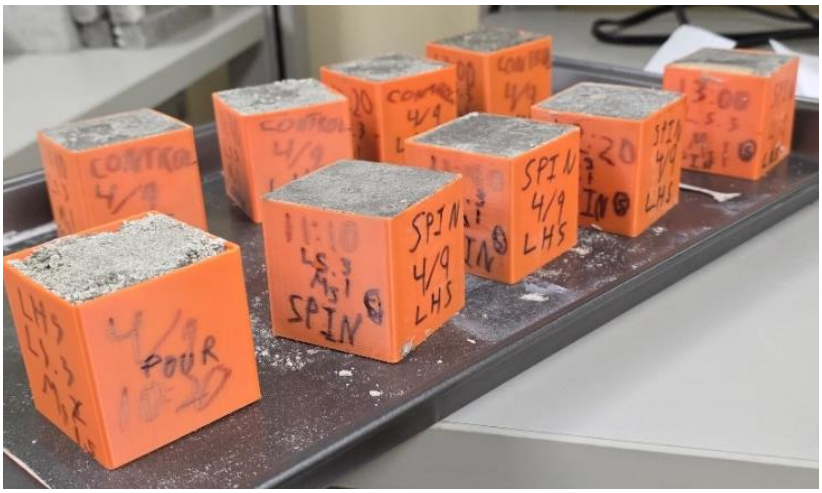

Figure 16: ASTM C109 Centrifuged compressive test geopolymer molds with corresponding controls

4.3.3 Variability in regolith simulant

It is important that researchers are aware of the possible discrepancy between the material properties of regolith simulant ordered from one vendor at different times. Space Resources Technologies provides regolith simulant to NASA, ESA, JAXA and the UAE and their product has been used to publish scientific work in more than 300 publications ("Publications", Space Resource Technologies, 2023). According to the website and confirmed with personal correspondence regarding LHS-1, as of 2025 the vendor has used same source materials and processing methods for LHS-1 since 2023. Despite this, the difference between a batch from an order received in February 2025 and an order received in April 2025 was substantial. The motivation of this experiment was to test the consistency of compressive strength and microstructure from different shipments of the same simulants. In all samples tested, the liquid/solid ratio was 0.3 and the silica modulus was 1. They were all placed in an oven for 3 days in a 3-D printed ABS polymer mold at 70°C, and allowed to continue in the oven after being demolded for 10 more days. These samples underwent a treatment identical to the controls of the

centrifugation experiment and were tested for compressive strength with SEM microstructure analysis. It is also important to note that on the Moon and Mars, like Earth, there is also local variation due to a variety of factors including geology, erosion and exposure to the Sun. Therefore, researchers preparing for space settlement should understand the differences between samples of regolith simulant to adequately to account for the differences that will inevitably be found between samples of actual regolith.

4.3.4 Concrete mixer designs

In 2024 the author was the project lead of a team of students who attempted to prototype a lunar concrete mixer based on the principles outlined in this thesis. It consisted of a centrifuge where concrete is mixed in a central chamber. In this design, the lunar regolith simulant is mixed with an alkali activator solution until the geopolymer is sufficiently homogenous. Then, doors lining the interior of the chamber open to expose brick molds, and the mixing chamber spins to fling the wet concrete into the molds with centrifugal force. The centrifuge spins until the geopolymer bricks have fully cured. In a prospective system design, it is envisioned that the water evaporated during the curing process could be recovered and recycled for subsequent batches, thereby enhancing resource efficiency as the finished tiles are extracted from the chamber. While the team was unable to construct a pressurized centrifuge designed to operate in a vacuum chamber, this was the first stage of development that could inform researchers interested in building upon a device based on these concepts.

The approach to designing a concrete mixer on the Moon would have to be fundamentally different because of how different circumstances are on Earth. In conventional concrete mixing,

the user typically loads portland cement, sand, water, and aggregate into a rotating drum. As the drum turns, portions of the unmixed concrete adhere to the chamber walls and are lifted upward by rotational motion. Once the gravitational force exceeds the adhesive force holding the material to the wall, the mass falls and collides with other material within the drum. This process enables the mixture to fold and intermix, promoting homogenization. The primary mechanism driving the mixing action in addition to the rotation of the drum, is gravity. Therefore, in a weaker gravity environment, concrete mixers would have to function differently. Normally the concrete is mixed in one container and then is transferred to the mold or pour location.

On the Moon, there is less gravity to use in the mixing process so a more efficient and effective method of agitation would be to mechanically drive the liquid, the alkali activator and the binder, lunar regolith simulant together. To respond to this challenge, there is a prominent mixer blade rotating axially in the center that reaches all parts of the mixing volume. Contact with the vacuum of space risks water boiling away before the curing process can take place, so it is therefore reasonable to consider mixing and curing the concrete in the same vessel, or an adjacent one. To respond to this challenge, the molds to make the concrete tiles are adjacent to the mixing volume, separated by doors that open when the mixing process is complete. The rotation of the vessel and subsequent outward centrifugal force is central to the design in two ways. This acts a means to transport the slurry away from the mixing volume into the molds, and as a directional force to allow air bubbles that form during the curing process a means to escape the slurry.

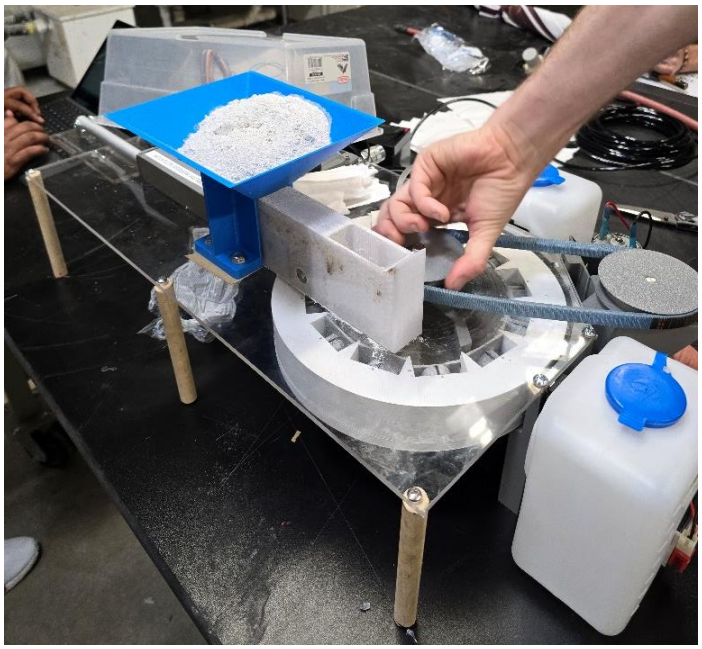

Figure 17: 2024 NASA MINDS Concrete Mixer testing

The 2024 mixer in Figure 17, based on the rendering from Figure 18, was unable to operate autonomously as a fully functional concrete mixer, and was made of additive manufactured polymer filament so repeated use was not possible, but the proof of concept was achieved. After the 2024 NASA MINDS project, an attempt was made to expand on this concept to test the chamber alone using a drill press to turn the mixer blade, shown in Figure 19. This work looked at a simplified version of the mixer to verify functionality and test various metrics, especially the porosity of the specimen manufactured. The doors that covered the molds were unable to contain the liquid sodium silicate meant to react with the regolith simulant to form concrete. Because the alkali activator, which at the time was only sodium silicate, did not mix properly with the simulant. The homogenously mixed concrete slurry was added to a sample holder that contained molds. The samples were both spun for 3 hours, but because of the fracture of a polymer mixing blade, poured at different intervals before centrifugation.

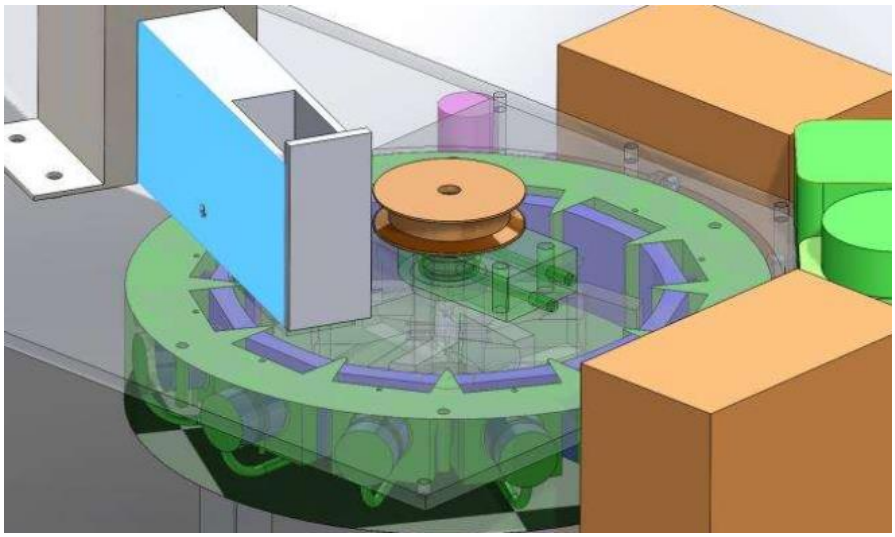

Figure 18: CAD Rendering of Concrete Mixer

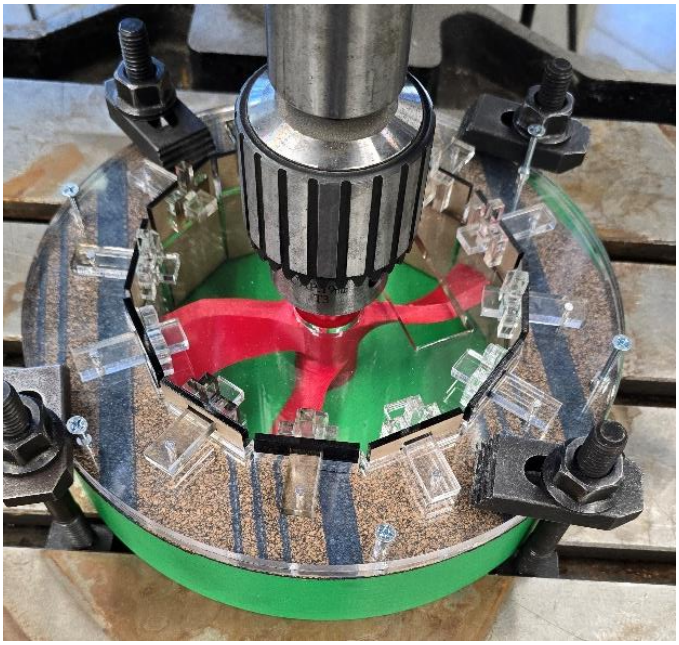

Figure 19: Chamber on a Drill Press Before Mixing

As shown in Figure 20, the sample at the top of the image was poured one hour prior to centrifugation, while the sample at the bottom was poured only minutes before. Although the top sample did not retain a uniform brick shape, it exhibited more thorough mixing, as geopolymerization had progressed for an hour before centrifugal force was applied. In contrast, the bottom sample showed drastic evidence of incomplete mixing, with visible separation between the alkali activator and simulant, and a distinct particle size gradient from coarse to fine. These observations motivated the centrifugation experiment detailed in subchapter 4.3.2, which aimed to determine the optimal curing duration prior to the application of centrifugal force.

Figure 20: Geopolymer poured 1 hour before centrifugation (top) Geopolymer poured minutes before centrifugation (bottom)

The centrifuge, seen in Figure 21 was fashioned with a drill press, spinning at a rate of 364 rotations per minute (rpm), with tiles 9.4 cm from the center. This resulted in a relative centrifugal force equivalent, or ‘g’ force of 13.9 as seen in Equation 2.

Figure 21: Chamber in Centrifuge Configuration

$$RCF = \frac{\left(2\pi^2 * r * RPM^2\right)}{3600 * g}$$

Equation 2: Relative Centrifugal Force

This allowed for samples to be flung to the walls of the mixer with enough force to be perpendicular to the ground. This speed was necessary to dominate Earth gravity and assure that rectangular tiles and cubic testing samples could be produced. In addition, researchers have found increased strength of geopolymer concrete increases when spun at higher centrifugation speeds,

with a compressive strength on 71.8 MPa when spun at 5000 rpm, which was 133.8% stronger than samples not exposed to centrifugation. According to Li et al. (2024), higher centrifugation rates enhance the reaction kinetics and crosslinking of gel products, which are critical for effective geopolymerization. However, their study utilized ground granulated blast furnace slag, a material with a significantly narrower particle size distribution—characterized by d_{10}, d_{50}, and d_{90} values of 2.45 μm, 8.21 μm, and 23.52 μm, respectively. While chemically suitable for geopolymerization, slag differs substantially from regolith simulants, which exhibit broader and more heterogeneous particle size distributions. As a result, applying high centrifugation rates directly to regolith-based mixtures would lead to a gradient of particle size, as seen in Figure 20. To mitigate this effect, centrifugation speeds should be catered to the consistency of each slurry, and a controlled curing period should precede centrifugation to allow for initial gel formation and improved homogeneity.

5. RESULTS AND DISCUSSION

5.1 Preliminary compression strength analysis

Due to the limited sample size and absence of repeated trials because of the high cost of regolith simulants, these results should not be interpreted as definitive or broadly generalizable within geopolymer research. Corresponding with data from other researchers in the field, (Dawood et al., 2024) the data gathered from this phase of the work show emerging patterns but did not show strong correlations from the compressive strength tests. Rather, this preliminary study aimed to identify an adequate mixture for subsequent centrifugation testing. For this purpose, qualitative data was important in addition to the quantitative compressive strength test data. These initial findings offer insight into the behavior of various combinations of silica, sodium hydroxide, and regolith simulants, based on which further optimization can take place to improve desired parameters. While a full 28-day curing period was not pursued, the objective was not to identify the highest-strength formulation, but to begin to understand material trends and performance characteristics. Weakly correlated but still discernible qualities emerged that support further discussion and subsequent optimization. This section specifically investigates how variations in silica modulus and liquid-to-solid ratio influence early compressive strength.

Although extended curing can enhance mechanical performance, mixtures that demand prolonged curing durations are less practical for in-situ applications. This underscores the importance of early-stage performance evaluation in material optimization. The study prioritized formulations compatible with centrifugation, which necessitate sufficient viscosity. Highly flowable mixtures were found to be prone to significant particle segregation under centrifugal force and based on experimental observations, exhibited longer curing times. This preliminary analysis

was conducted in parallel with a study by another master's student in the research group, Catalina Gonzales, on the suitability of additive manufacturing using simulant geopolymer.

Portland cement is typically 19Mpa after 7 days, rising to around 35MPa after 28 days for Type I, the most basic type of cement (Pavement Interactive, 2025), and the highest compressive strength from this study was 5.32 mPa after 14 days in the preliminary test. Also, this strongest sample was too viscous to be workable for the purposes of this experiment. Based on workability, a L/S of 0.3 and silica modulus of 1 was chosen, which in later experiments, detailed in sections 4.3.3 and 5.4, was found to have a 25 MPa compressive strength after 13 days. A contributing factor to the reduced strength values may have been the curing method: although some samples were ready to be demolded earlier, all specimens remained in their molds for the full 14-day period to ensure consistency, resulting in air exposure on only one face of each cube. When Mars regolith simulant geopolymer was tested for this purpose, all liquid combinations when tested in practice were appropriate for additive manufacturing, but the adhesive properties would be a challenge for centrifugation. To save material for the building and testing additional samples for 3-D printing, trails were limited of martian regolith simulant geopolymer. For this thesis, additional simulant was not available for martian regolith simulant centrifugation tests. As a result, less data points are available for martian geopolymer, but the wide variety of tests for lunar geopolymer can offer insight into next steps for further research, which will be expanded upon in later chapters of this thesis. The compressive strengths of the preliminary samples are shown in Table 3.

Table 3: LHS compressive test results with corresponding liquid-solid ratios and silica moduli

Sample Number	Liquid/Solid Ratio	Silica Modulus	Compressive Strength (MPa)
LHS_0.2_1.0	0.2	1.0	**5.32**
LHS_0.2_1.5	0.2	1.5	4.94
LHS_0.2_2.0	0.2	2.0	1.42
LHS_0.25_1.0	0.25	1.0	2.5
LHS_0.25_1.5	0.25	1.5	4.79
LHS_0.25_2.0	0.25	2.0	3.15
LHS_0.3_1.0	0.3	1.0	1.69
LHS_0.3_1.5	0.3	1.5	1.5
LHS_0.3_2.0	0.3	2.0	3.52
LHS_0.4_1.0	0.4	1.0	1.76
LHS_0.4_1.5	0.4	1.5	1.03
LHS_0.4_2.0	0.4	2.0	2.01
LHS_0.4_2.5	0.4	2.5	1.07
LHS_0.4_3.0	0.4	3.0	2.96

For LHS-based geopolymers, the relationship between compressive strength, liquid-to-solid ratio, and silica modulus appears non-linear and moderately interdependent. As shown in Figure 22, at a silica modulus of 1.0 and 1.5, compressive strength decreases with an increasing liquid-to-solid ratio, likely due to excess water diluting the gel network and weakening the matrix. In contrast, at silica modulus values of 2.0, strength increases with a higher liquid-to-solid ratio, suggesting that greater fluid content may enhance dissolution, contact between the silica of the fluid and alumina of regolith resulting in gel formation when sufficient silicate is available.

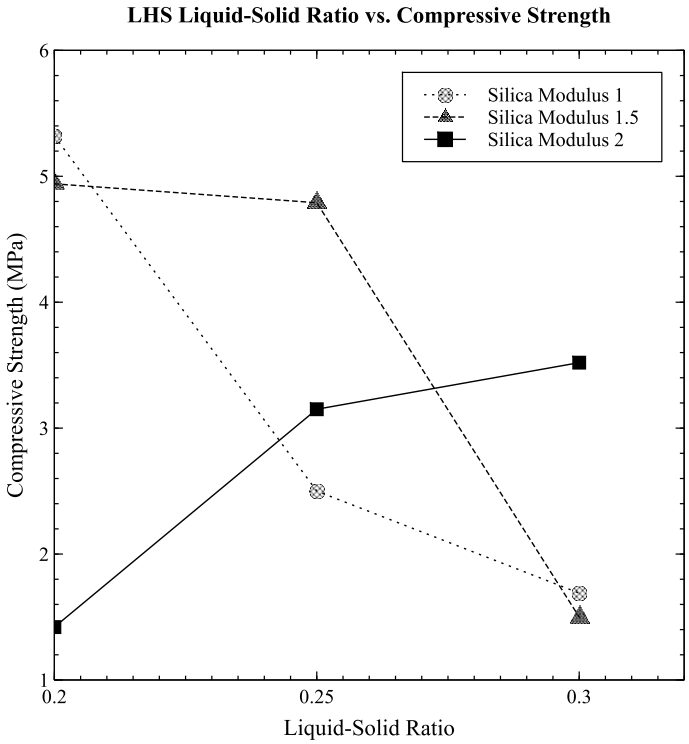

Figure 22: Line graph of Liquid-Solid ratio and Compressive Strength results

As shown in Figure 23, the results of a correlation of silica modulus and compressive strength when controlling for liquid solid ratio were less conclusive and more trials are needed to draw definitive conclusions.

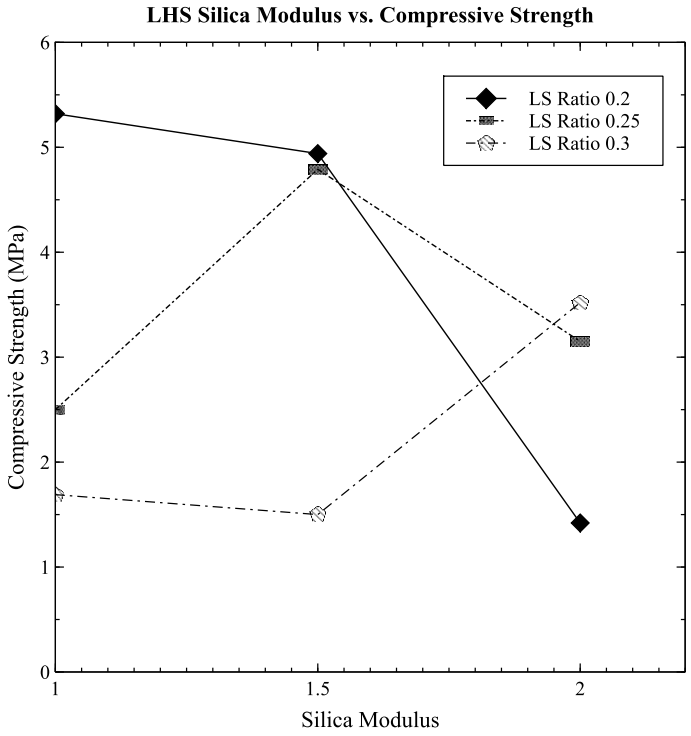

Figure 23: Line graph of LHS Silica Modulus and Compressive Strength results

In the statistical analysis of the LHS seeking correlations among attributes, the Response Surface Method was used to seek trends, interactions, and optimal regions. This model helps to analyze how two or more input variables (liquid-to-solid ratio and silica modulus) affect an output variable (compressive strength). The setting of the model was uncoded design, backward elimination, at alpha=0.20 (80% confident interval). The use of uncoded values, refers to the actual values (L/S = 0.25 or SM = 1.5) which are better for understanding real-world impact, as opposed to standardized values (like from 0 to 1) which are easier for optimization. Backwards elimination is used to simplify the model by removing the least useful variables, based on p-values, keeping only those that seem to meaningfully affect the outcome. Because the sample size is small and the goal of the study is to look for exploratory patterns, not final conclusions, the alpha (α) level, or

threshold for statistical significance, commonly set at 0.05 (95% confidence), was set to 0.20, meaning 80% confidence was permissible.

The statistical output from Minitab as shown in Figure 24, where the regression model yielded an R^2 of 49.32% with an 80% confidence interval, indicating that roughly half of the variability in compressive strength is explained by the model. However, the adjusted R^2 of 34.11% suggest limited generalizability and potential overfitting due to data variability or sample size.

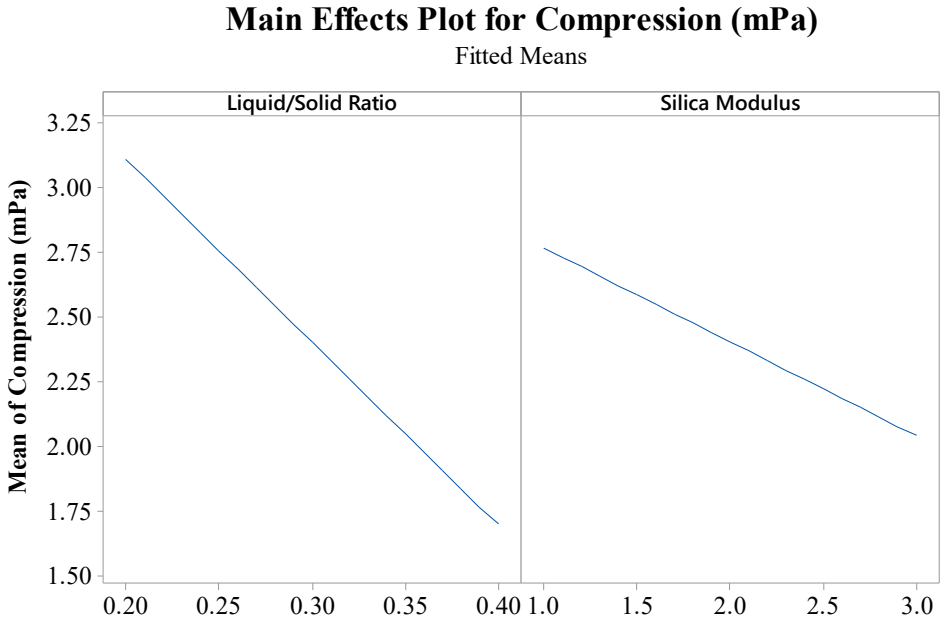

Figure 24: LHS Variance analysis showing weak correlations of compressive strength, liquid-solid ratio and silica modulus

The interaction plot, shown in Figure 25, depicts how the effect of one variable depends on the level of another, shows a moderate interaction between liquid/solid ratio and silica modulus. Although not statistically conclusive ($p = 0.144$), the non-parallel lines in the plot indicate that the effect of liquid/solid ratio on strength may vary depending on the level of silica modulus. Specifically, at lower silica modulus, strength tends to decline more steeply with increasing L/S

ratio, while at higher silica modulus, this trend appears less pronounced. This points to a potential synergistic or moderating relationship between the two variables, also warranting further study with a larger data set.

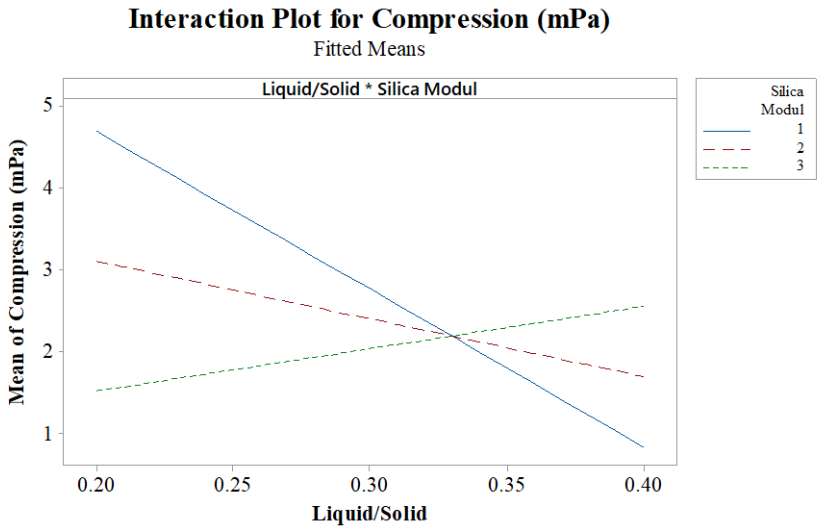

Figure 25: LHS Variance analysis showing weak correlations of compressive strength, liquid-solid ratio and silica modulus

As can be seen in the analysis of variance of Table 4, neither liquid-to-solid ratio ($p = 0.199$) nor silica modulus ($p = 0.608$) were individually significant predictors of strength, but their interaction ($p = 0.144$) showed potential relevance, highlighting the importance of evaluating these parameters jointly. Overall, while the statistical correlation is weak, the experimental results suggest that an optimal silica modulus near 1.5, in combination with a moderate to high liquid-to-solid ratio (e.g., 0.3), may offer improved compressive strength. Further testing with broader datasets is needed to validate and refine these relationships. The overall model has value as an F-Value above 2.5 with a P-Value below 0.20 can be seen as suggestive. The adjusted sum of squares describes how much variation that factor affects compressive strength with a larger number meaning the factor is more significant. The adjusted mean square shows the average variation per degree of freedom which is used to calculate the F-value. The F-value can be interpreted as a signal to noise ratio with a higher number meaning the factor more likely affected strength. The P-value is the probability that the effect is just random noise. If P is less than alpha, which for this study

was deemed to be 0.20, the factor is acceptable enough to be considered statistically significant. When all these elements of this analysis of variance table are taken into account, the following conclusions be drawn. While the silica modulus alone is not significant, and the liquid-to-solid ratio alone is weakly significant, these two factors combined show some interaction which is worth noting. This is reinforced by the linear effect of the two main variables combined, the liquid-to-solid ratio and silica modulus, which together are weakly significant. The liquid to solid ratio alone is barely significant to compressive strength, suggesting that a thicker paste may make a stronger material. The relationship between silica modulus alone and compressive strength is not significant demonstrated by the F value at 0.28, far below the 2.5 threshold and the P value at 0.608 far above the 0.20 threshold.

Table 4: Analysis of Variance for LHS regarding the effect of Silica Modulus and Liquid-to Solid Ratio on Compressive Strength

Analysis of Variance					
Source	Degrees of Freedom	Adjusted Sum of Squares	Adjusted Mean Square	F-Value	P-Value
Model	3	13.8715	4.6238	3.24	0.069
Linear	2	5.9774	2.9887	2.1	0.174
Liquid/Solid Ratio	1	2.6974	2.6974	1.89	0.199
Silica Modulus	1	0.3992	0.3992	0.28	0.608
2-Way Interaction	1	3.576	3.576	2.51	0.144
Liquid/Solid Ratio*Silica Modulus	1	3.576	3.576	2.51	0.144
Error	10	14.2561	1.4256		
Total	13	28.1276			
Model Summary-		Rsq = 0.49	Adj = 0.34		
S	R-sq	R-sq(adj)	R-sq(pred)		
1.19399	49.32%	34.11%	0.00%		

For SP2-based geopolymers, the results as shown in Table 5 were also relatively mixed as compressive strength was influenced by a complex interaction between liquid-to-solid ratio and silica modulus. In this case the regression analysis did reveal a statistically significant linear relationship between silica modulus and compressive strength ($p = 0.029$), with the model explaining 46.91% of the variance (R^2) and an adjusted R^2 of 40.27%, indicating a moderate correlation.

Table 5: SP2 compressive test results with corresponding liquid-solid ratios and silica moduli

Sample Number	Liquid/Solid Ratio	Silica Modulus	Compressive Strength (MPa)
SP_0.2_1.0	0.2	1	0.81
SP_0.2_1.5	0.2	1.5	0.92
SP_0.2_2.0	0.2	2	1.63
SP_0.25_1.0	0.25	1	0.63
SP_0.25_1.5	0.25	1.5	0.9
SP_0.25_2.0	0.25	2	0.93
SP_0.3_1.0	0.3	1	0.71
SP_0.3_1.5	0.3	1.5	1.94
SP_0.3_2.0	0.3	2	**2.16**
SP_0.3_1.0	0.4	1	0.64

As shown in Figure 26, the data indicates that SP2 mixtures benefit from higher silica modulus only when the liquid-to-solid ratio is also elevated. At a silica modulus 2.0 and liquid-to-solid ratio 0.3, the highest strength is achieved (~2.16 MPa), while mixtures with a lower silica modulus or intermediate liquid content underperform.

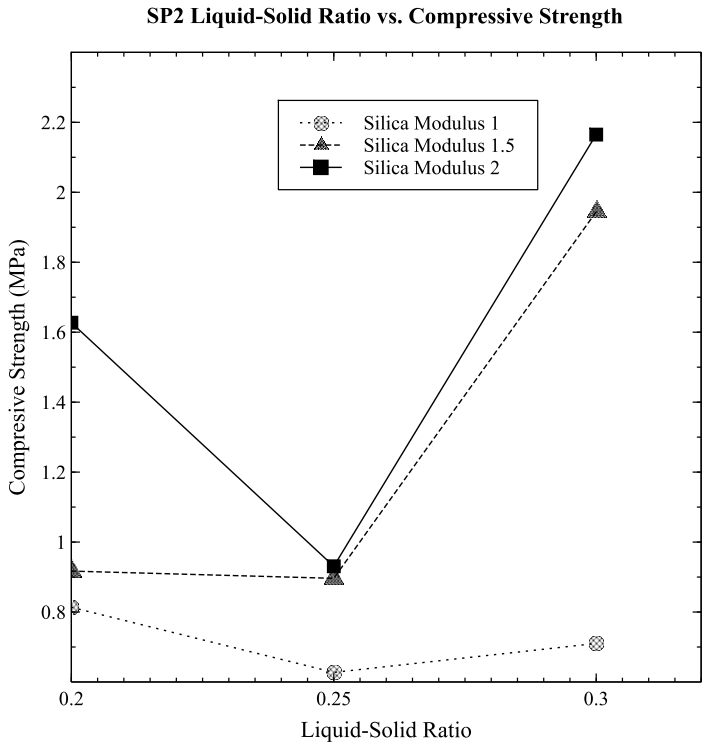

Figure 26: SP2 Compressive test results with corresponding liquid-solid ratios and silica moduli

As seen also in Figure 27, both graphical trends support this result as both 0.2 and 0.3 liquid-to-solid ratios show a clear increase in compressive strength as silica modulus increases. In contrast, at a ratio of 0.25, strength remains relatively flat across silica modulus values, suggesting a mismatch in water-to-activator balance that limits reaction efficiency. These results suggest that SP2 requires both sufficient liquid for workability and high reactive silica content to overcome its lower inherent reactivity. While predictive power remains limited (R^2(pred) = 16.13%), the consistent strength gains at higher levels confirm silica modulus as an important key parameter in optimizing SP2 geopolymer performance.

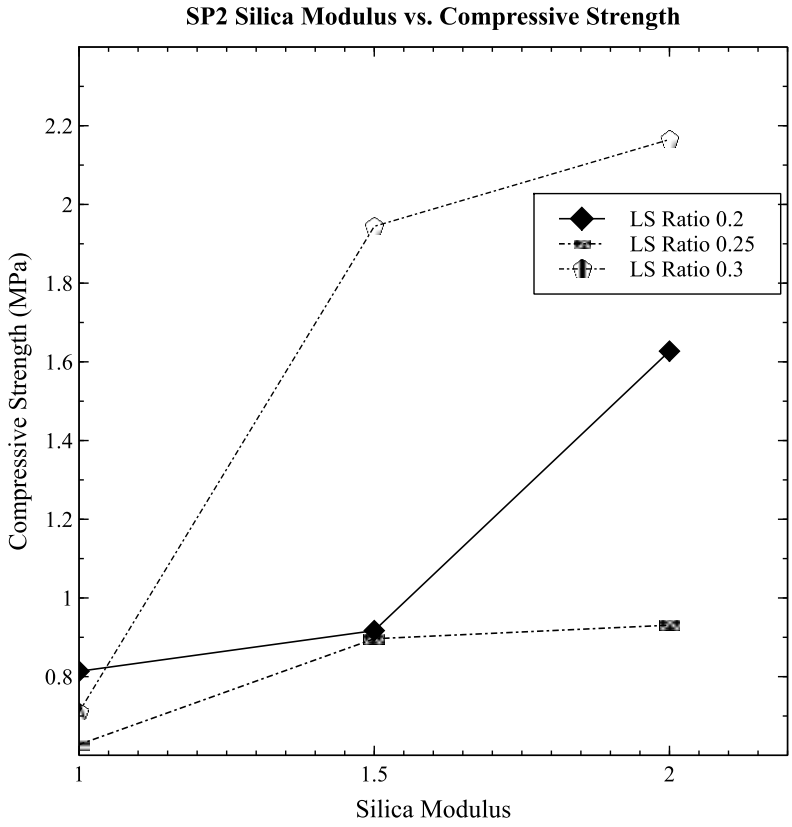

Figure 27:Line graph of LHS Silica Modulus and Compressive Strength results

The 14-day preliminary analysis of compressive strength of lunar simulant geopolymers did not yield highly conclusive results, but certain deductions could be made. LHS Simulant can achieve >5 MPa compressive strength with an optimized liquid-solid ratio of 0.25–0.3 and a silica modulus of roughly 1.5–2. With Lunar South Pole Simulant, there is a stronger effect of silica modulus than liquid-solid ratio overall. SP2 Simulant produces lower strengths (~2 MPa max) and needs both higher liquid-solid ratio and higher silica modulus to perform adequately. LSP-2's coarser particles and higher levels of CaO and Na_2O likely result in rapid initial setting but delayed final curing. The SP2 geopolymer formulated in this thesis also had poor internal consolidation, frequently producing samples that appear hard externally but remain soft or brittle inside. The

combination of these factors explains the difficulties in extrusion, stacking, and achieving uniform strength in SP2-based mixes. The fact that not all the samples were fully cured calls into question any conclusions that one may draw from correlations with silica modulus, liquid-to-solid ratio and compression strength. However, enough data was gathered to know what combination of factors was needed to proceed with further experimentation. The point of the study was not to optimize the chemical reagents for compressive strength, but to find what mixture could work in a concrete mixer and centrifuge.

Despite the lack of strongly conclusive data regarding the relationship of silica modulus, liquid-to-solid ratio and compressive strengths in lunar regolith simulant, insight was gained into the behavior and application of the materials. Based on the results of this short duration study, LHS is better suited for structural applications, while SP2 may need enhancement like additives, fibers or different processing methods like sieving to closely monitor particle size distribution. In short, LHS-1 is a more efficient and reactive simulant for alkali activation, achieving higher strengths with less silicate and a lower liquid-solid ratio. LSP-2 requires higher liquid-solid ratios and increased silica modulus to compensate for its coarser grain size and lower reactivity but still underperforms in strength. LHS-1 can provide moderate to high strength with manageable extrusion behavior when silica modulus, liquid-solid ratio and timing are carefully balanced. SP2 may require different curing environments elevated temperature, molds that have increased ventilation, sieving to adjust particle size distribution or modifications to activator formulation to reach comparable performance. The results affirm that particle size and aluminosilicate reactivity dominate geopolymer strength trends, though alkali content and mix balance are also critical.

Table 6: MGS-1C Compressive test results with silica moduli at a 0.4 liquid-solid ratio

Sample	Liquid/Solid Ratio	Silica Modulus	Compressive Strength (MPa)
MGS_0.4_1.0	0.4	1.0	3.43
MGS_0.4_1.5	0.4	1.5	5.5
MGS_0.4_2.0	0.4	2.0	**5.91**
MGS_0.4_2.5	0.4	2.5	2.79
MGS_0.4_3.0	0.4	3.0	5.65

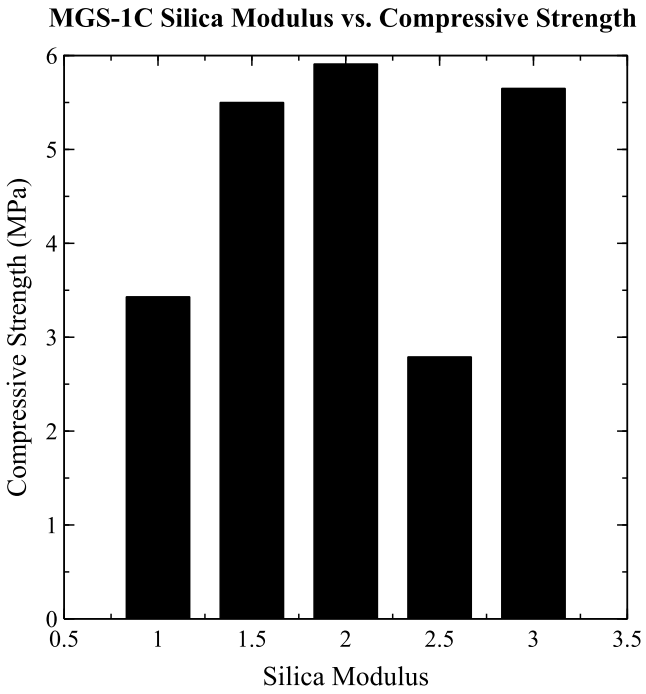

Figure 28: Bar graph of MGS-1C Compressive test results with silica moduli at a 0.4 liquid-solid ratio

From anecdotal evidence, it was clear that the prominence of clay sized particles drastically increased the ability of the material to absorb liquid and the lower liquid-to-solid ratios would not be successful. Consequently, the compressive strength of MGS-based geopolymers was evaluated at a constant liquid-solid ratio of 0.4 while varying the silica modulus from 1 to 3. The results

show a non-linear trend, with strength peaking at a silica modulus of 2.0 (5.91 MPa) before slightly decreasing or plateauing. This behavior can be explained in part by the ultrafine particle size distribution of MGS (D50 = 14 μm), which enhances early reactivity and dissolution of aluminosilicate phases. Additionally, MGS-1C's mineralogical composition—rich in smectite (20.6%) and hydrated phases like ferrihydrite, hydrated silica, and Mg-sulfate—contributes to rapid initial geopolymerization, but may also introduce intensive crack formation and structural instability at higher silica loadings. (Karl et al., 2020) At a silica modulus of 1, the mix likely lacks sufficient silicate ions for effective geopolymerization cross-linking of the aluminosilicate, resulting in a lower strength of 3.43 MPa. Strength increases significantly at a silica modulus of 1.5 and 2.0, suggesting an optimal silica content that promotes gel network formation and densification of the matrix. Beyond silica modulus of 2, the compressive strength declines at a silica modulus of 2.5 (2.79 MPa), possibly due to an oversaturation of unreacted silicates or poor phase compatibility between excess sodium silicate and the high clay content of the simulant, which can lead to porosity or efflorescence. However, at a silica modulus of 3, strength increases again to 5.65 MPa, which may indicate that under some conditions, excess silicate begins to reintegrate into the structure as the mix rebalances chemically. Nevertheless, the variability at high silica moduli points to the importance of achieving a precise silica balance in clay-rich regoliths that may resemble MGS. In this case one cannot compare our results of lunar and martian regolith simulant geopolymer not only because the simulants are distinct, but because the MGS had fully cured after 14 days and the lunar samples had not. In addition, unlike the lunar samples, the MGS had significant efflourecence which weakens mechanical strength.

There are several factors that can affect the strength of specimen, and this work controled for factors and varied others individually. Vibration can affect a viscous sample in different ways than a highly fluid sample, so no samples were subjected to vibration before curing. It is worth noting that geopolymers can gain strength as they dry in early stages, particularly when excess water evaporates and geopolymerization progresses. On the other hand, uncontrolled drying may cause shrinkage or microcracking that can compromise strength. In our study, the cube molds were exposed on top, preventing the other 5 sides from accessing air. The shape of the mold along with the timing and manner of demolding could significantly affect results. Some samples cure faster and can be removed from their molds sooner to increase the exposed surface area to allow for more rapid curing. However, if samples are removed prematurely, damage to the sample can result, voiding the experiment. To avoid this problem and analyze all samples in a consistant manner, all remained in molds until the compressive test. A particle size distribution dominated by fine particles will result in a geopolymer with higher compressive strength, but the goal was to understand the material, not attempt to make the strongest geopolymer possible, so no samples were sieved. Porosity, microstructure, air voids, mix design, simulant type, temperature and curing time are all factors that can affect compressive strength and all are interrelated. To determine which factors were more dominant than others, patterns are determined from samples that have attributes in common. Different varients were composed while others were controled to investigate which may be more influential. Porosity and air voids are influenced by the mix design so to optimize strength especially in viscous mixes, vibration and centrifugation can result in a stronger sample. A simulant with coarser material like SP2 was consistently weak so this was determined to be a dominating factor. Regardless, the lack of conclusive evidence and high statistical correlation of

all factors explain why this part of the thesis remains a preliminary analysis and not a defining feature of this work.

5.2 Preliminary workability and printability analysis

The workability and printability of the preliminary samples were evaluated primarily through the lens of extrudability, which served as a proxy for assessing suitability in additive manufacturing applications using geopolymer concrete for off-Earth construction. In this context, extrusion-based methods are critical for fabricating structural components on the Moon and Mars. The qualitative assessment of workability provided insight into the rheological characteristics of each simulant when activated with varying silica moduli and liquid-to-solid ratios. For geopolymer composites to be suitable for centrifugation, especially for forming dense, void-free bricks, the material must have a balanced viscosity. It should be high enough to maintain the integrity of the polymeric gel matrix, but low enough to allow entrapped air to escape under centrifugal force. Excessive viscosity, influenced by mix proportions and the time between mixing and centrifugation, can restrict flow and prevent the specimen from responding effectively to applied g-forces. Conversely, a slurry with excessive fluidity may undergo particle segregation, forming a non-uniform gradient from the center to the periphery of the specimen. Therefore, understanding and controlling the fresh-state behavior of the geopolymer mix is essential for identifying formulations that are mechanically stable, centrifugation-compatible, and conducive to successful in-situ fabrication under simulated lunar or martian conditions. Table 7 shows workability results with observations during compression tests and the manner at which fractures took place. In addition to knowing the condition of the geopolymer upon being poured, the degree of curing after 14 days and notable textures of surfaces were recorded. Workability and printability analysis was

the primary focus of the thesis “Mechanical and Seismic Performance of Extraterrestrial Geopolymers for Lunar and Martian 3D-Printing Applications” authored by Catalina Gonzales. So while these aspects are mentioned here, an extensive discussion is out of the scope of this thesis.

Table 7: LHS Qualitative workability results with corresponding silica moduli and liquid-solid ratios

Simulant	Liquid/Solid Ratio	Silica Modulus	Texture upon mixing	Notes from Compression Test
LHS_0.2_1.0	0.2	1.0	Too dry; extruded in fragments	Fully cured but crumbled near base
LHS_0.2_1.5	0.2	1.5	Poor cohesion and brittle; low workability	No strength data provided
LHS_0.2_2.0	0.2	2.0	Poor cohesion and brittle; failed to form paste	Brittle at base but structurally cohesive
LHS_0.25_1.0	0.25	1.0	Extruded consistently; requires layered mixing	Many voids after demolding; began setting during forming
LHS_0.25_1.5	0.25	1.5	Dried rapidly; limited workability	Cast but weak cohesion
LHS_0.25_2.0	0.25	2.0	Poor cohesion and brittle; low flowability	Retained rigid shape; damp interior observed when fractured
LHS_0.3_1.0	0.3	1.0	Flowable with potential interlayer drying	Slightly damp internal surface
LHS_0.3_1.5	0.3	1.5	Overly fluid; failed to stack and remained unset after 1 hour	Slightly damp internal surface
LHS_0.3_2.0	0.3	2.0	Low workability; extruded in fragments	Retained rigid shape; damp interior observed when fractured
LHS_0.4_1.0	0.4	1.0	Highly fluid; unable to retain shape	Slightly damp internal surface
LHS_0.4_1.5	0.4	1.5	Highly fluid; unable to retain shape	Slightly damp internal surface
LHS_0.4_2.0	0.4	2.0	Highly fluid; unable to retain shape	Slightly damp internal surface
LHS_0.4_2.5	0.4	2.5	Balanced cohesion and flowability	Slightly damp internal surface
LHS-_0.4_3.0	0.4	3.0	Excessive fluidity; unable to retain shape	Surface film formation observed

LHS could be seen as an intermediary in between MGS-1C, which is highly suitable for extrusion, and SP2 which would require significant modification to be suitable. This is likely a function of the LHS particle size being in between the two simulants. On one extreme, SP2 is not

extrudable and no silica modulus nor liquid-solid ratio made the simulant easily suited to additive manufacturing. On the opposite end is MGS-1C where every tested combination was suitable. LHS bridged this gap with workability being highly dependent on liquid-solid ratio. At low ratios (0.2), mixtures are dry, brittle, and difficult to extrude. The best extrusion and handling were observed at a 0.25 liquid-solid ratio with silica modulus 1, though compressive strength was moderate (~2.5 MPa). The highest compressive strength (5.32 MPa) occurred at a 0.2 liquid-solid ratio with silica modulus of 1, but the mixture was dry and brittle and therefore unsuitable for extrusion. Higher silica moduli at a liquid-solid ratio of 0.4 show unsuitability with low strengths and cohesion due to excess liquid and dilution. In summary, according to these tests, LHS-1 requires a balance between cohesion and activator content. It might benefit from a moderate to higher liquid-solid ratio and lower to moderate silica modulus values (0.25–0.3; silica modulus = 1-1.5). However, as with all the data from this study, more repeated trials are needed to draw more conclusive evidence.

SP2 showed generally poor compressive strengths (<2.2 MPa in all cases), and poor internal setting across most mixtures. Workability varied drastically as can be seen in the SP2 compressive strength and workability results in Table 8. While a low liquid-solid ratio (0.2), and low silica modulus (1.0) had good flowability but remained soft inside; higher silica moduli led to brittle, non-extrudable pastes. Silica modulus of 2.0 with a liquid-solid ratio of 0.3 yielded the highest compressive strength (2.16 MPa) but was not extrudable and still soft inside after compression. SP2 seems to have low reactivity or insufficient cohesive gel formation, after 2 weeks of curing. The combination of coarse particles and high CaO/Na_2O likely causes early surface hardening while leaving the core under-cured. The most extrudable SP2 sample had a

lower silica modulus (1.0) and lower liquid-solid ratio (0.2), but a low compressive strength (0.81 MPa).

Table 8: SP2 Qualitative workability results with corresponding silica moduli and liquid-solid ratios

Simulant	Liquid/Solid Ratio	Silica Modulus	Texture upon mixing	Notes from Compressive Strength Test
SP_0.2_1.0	0.2	1.0	Good flowability, dries in minutes	Not as soft to the touch but not completely hardened
SP_0.2_1.5	0.2	1.5	Poor cohesion and brittle behavior, will not extrude	Soft interior
SP_0.2_2.0	0.2	2.0	Poor cohesion and brittle behavior	Completely hardened, no soft inside
SP_0.25_1.0	0.25	1.0	Excessive fluidity, will not stack	Very soft on the inside, falling apart in hand
SP_0.25_1.5	0.25	1.5	Poor cohesion and brittle behavior, will not extrude	Soft on the inside, adhered to compression platens
SP_0.25_2.0	0.25	2.0	Dries within seconds, did not extrude	Soft interior
SP_0.3_1.0	0.3	1.0	Excessive fluidity	Soft interior
SP_0.3_1.5	0.3	1.5	Too flowable, would not extrude fully towards the end	Adhered to the compression platens
SP_0.3_2.0	0.3	2.0	Excessive fluidity	Soft interior
SP_0.3_1.0	0.4	1.0	Excessive fluidity, will not stack	Soft interior

The superior performance of LHS-1 over LSP-2 in terms of workability and compressive strength can be attributed to its finer particle size, balanced anorthosite-basalt mineralogy, and moderate oxide composition. To address the reduced compressive strength of SP2 resulting from delayed curing, it is recommended that specimens be demolded promptly after casting to increase their exposed surface area and promote more effective drying. For the highly viscous and quickly unworkable samples due to high silica modulus and low L/S, vibration is recommended to reduce the possibility of large air pockets before the sample is fully cured. For a more flowable sample with a high L/S, vibration in not recommended as a distinct gradient of particle size can form with a film of fine particles on the top and coarse particles collecting at the bottom of the specimen.

MGS-1C is not a general-purpose simulant like LHS and SP2 but one catered to in-situ resource utilization, and therefore had drastically different characteristics as seen in Table 9. The clay enriched Mars simulant exhibited excellent extrusion characteristics across all samples at liquid-solid ratio of 0.4, regardless of silica modulus values. However, all samples showed significant shrinkage, air voids, and efflorescence post-curing. The highest compressive strength (5.91 MPa) occurred at silica modulus of 2.0, indicating this as a potential optimum for clay-based simulants. Compressive strength remained high at silica moduli of 1.5 and 3.0 (~5.5 MPa), suggesting resilience to silica modulus fluctuations, possibly due to high surface area and clay reactivity.

Table 9: MGS-1C Qualitative workability results with corresponding silica moduli at a 0.4 liquid-solid ratio

Simulant	Liquid/Solid Ratio	Silica Modulus	Texture upon mixing	Notes from Compressive Strength Test
MGS_0.4_1.0	0.4	1.0	Extrudes well and can stack but very strong adhesion to surfaces	Significant shrinkage and fractures throughout sample
MGS_0.4_1.5	0.4	1.5	Extrudes well and can stack but very strong adhesion to surfaces	Significant shrinkage and fractures throughout sample
MGS_0.4_2.0	0.4	2.0	Extrudes well and can stack but very strong adhesion to surfaces	Significant shrinkage and fractures throughout sample
MGS_0.4_2.5	0.4	2.5	Extrudes well and can stack but very strong adhesion to surfaces	Significant shrinkage and fractures throughout sample
MGS_0.4_3.0	0.4	3.0	Extrudes well and can stack but very strong adhesion to surfaces	Significant shrinkage and fractures throughout sample

The clay-rich composition of MGS-1C results in superior early plasticity and extrudability, but also the high surface area of the particles makes the resulting geopolymer vulnerable to shrinkage and ion migration. Efflorescence is pronounced due to high Na^+ mobility, especially

when silica modulus is not optimally matched. The best mechanical performance aligns with silica modulus of 2.0, where geopolymerization is balanced and shrinkage is minimized relative to strength.

For future construction on the Moon and Mars, large amounts of regolith should be sieved to carefully control the particle size distribution and prepare geopolymer. If an additive manufacturing approach is preferred, the particle size distribution should mirror that of MGS-1C, with fine silt to coarse sand and high proportion of particle sizes in between these grain sizes. More specifically, a multimodal distribution with peaks around 0.02, 0.01 and 0.1 mm with the presence of both fine particles, coarser grains and a substantial fraction of intermediate sizes. This will ensure that the resulting geopolymer is more extrudable, though lower resulting compressive strength and slurry adhesion within the machinery is likely to be a challenge. If an approach using stronger, standardized modular structural units like bricks or tiles are preferred, a particle size distribution like LHS is preferred. A unimodal particle size distribution centered around 0.07–0.09 mm, combined with a high clay content, is favorable for dense packing and enhanced strength during geopolymerization.

5.3 Effects of centrifugation on lunar simulant geopolymer

Of the eight samples cast and cured, six were used for testing; one control sample (the 170 minute sample) fractured during demolding. All three centrifuged samples exhibited higher compressive strength and distinct failure behavior compared to controls. The 100 minute specimens were selected for Scanning Electron Microscopy (SEM) due to their significantly different mechanical response and strength. In the graphical descriptions, sample names are abbreviated to indicate the number of minutes allowed to cure prior to centrifugation, followed by a 'C' for control samples (not centrifuged) or an 'S' for spun samples (centrifuged). In Figure 29, the centrifuged specimen on the right, labeled 'S 13:00,' exhibits visibly reduced porosity compared to the control sample on the left.

Figure 29: Control sample 60C (left) next to Centrifuged sample 60S (right), centrifuged 60 minutes after casting, demonstrating a reduction in porosity

Figure 30 presents SEM images of the control (left) and centrifuged (right) samples, each focused on a representative pore. The centrifuged sample exhibits more cohesive pore walls, while

the control shows loosely bonded particles along the perimeter, indicating improved microstructural integrity from centrifugation.

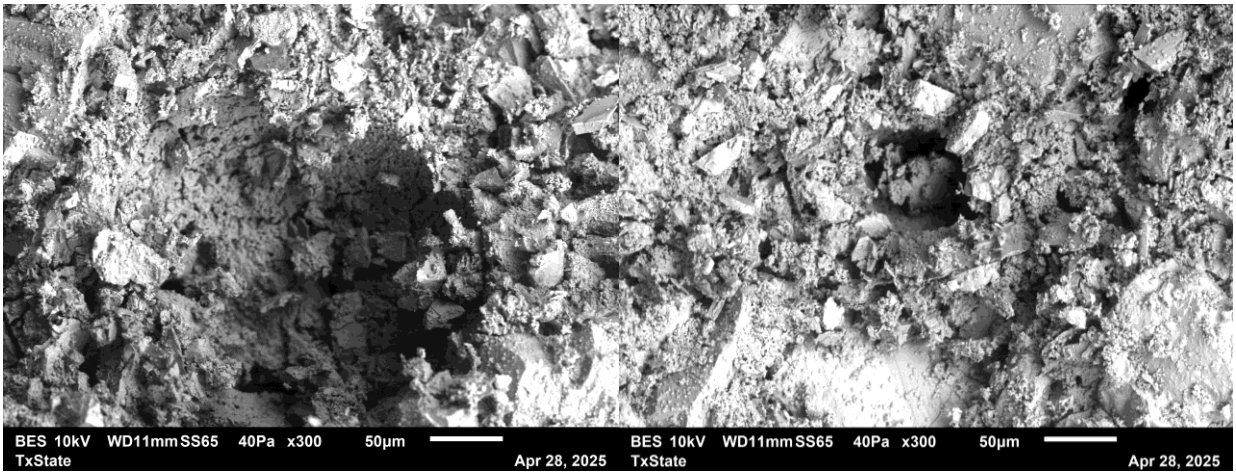

Figure 30 SEM image of Control sample 100C (left) and Centrifuged sample 100S (right) focused on a single pore.

From Figure 31, the control sample that has not been centrifuged has an even, random, scattered mix of a variety of different sized particles that are loosely connected. The rough surface does not show the very coarse sand grains of the LHS firmly embedded into fine particle paste when compared to the centrifuged samples.

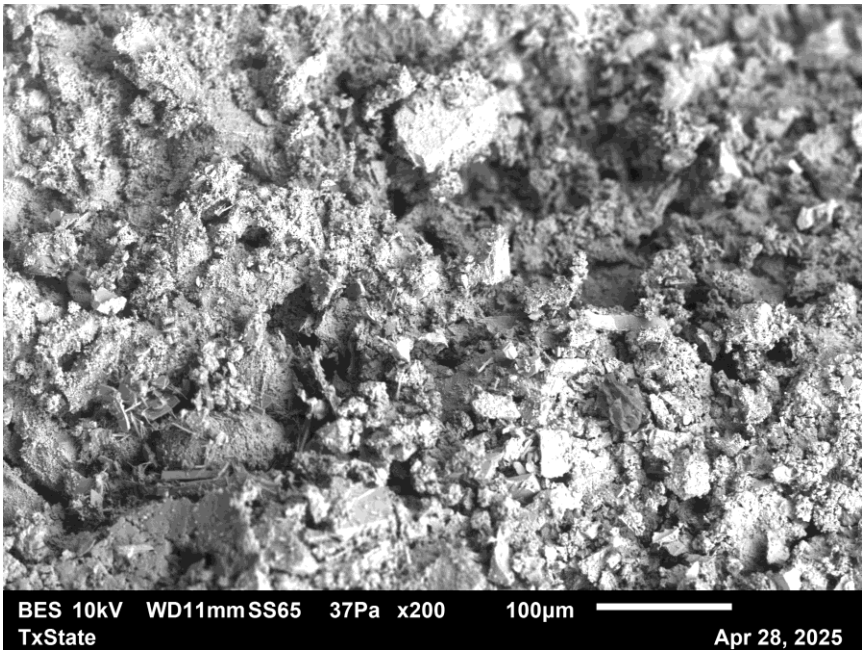

Figure 31 Control Sample 100C that was not centrifuged

In Figure 32, two images of a centrifuged geopolymer sample are presented. The image on the left shows the peripheral region further from the axis of rotation, where larger particles predominantly accumulated. The image on the right depicts the interior region closer to the axis of rotation, where finer particles were more concentrated. Although there is a noticeable gradient in particle size distribution—with coarser particles migrating outward and finer particles inward—the distribution remains fairly non-homogeneous, as both regions contain a range of particle sizes.

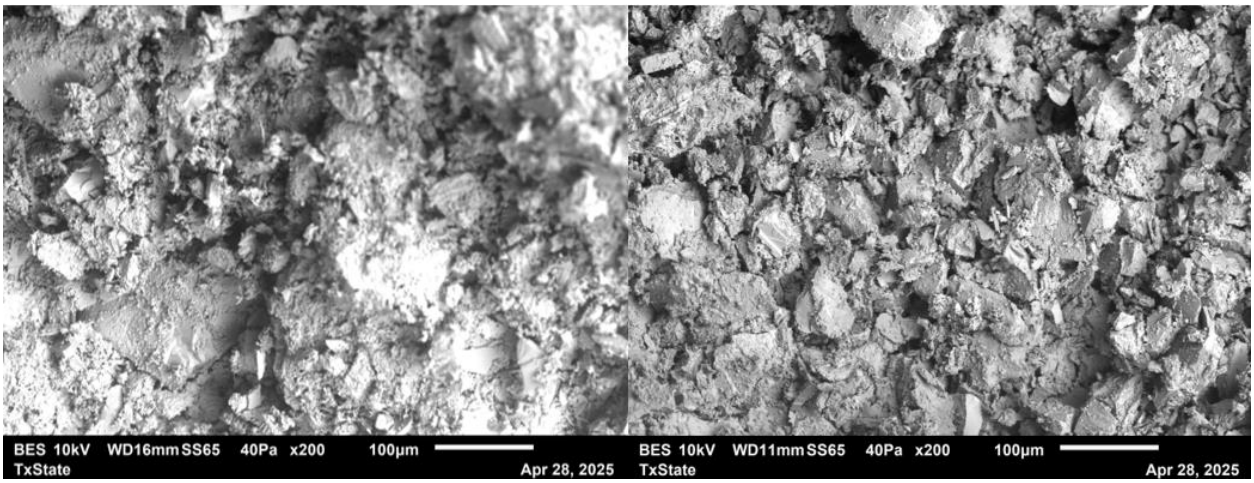

Figure 32: Centrifuged sample 100S on the coarse particle side (left) and centrifuged sample on the fine particle side (right)

This heterogeneity is beneficial for maintaining a functional Interfacial Transition Zone (ITZ), where fine particles enhance adhesion between aggregate and the surrounding geopolymer matrix. Both regions exhibit improved cohesion, strengthening bonds between particles and thereby improving compressive strength.

As can be seen in Table 10 and Figure 33, in the compressive strength tests, all centrifuged samples showed a slight increase in compressive strength. Centrifugation resulted in compressive strength increases of 1.47 MPa (15.39%) for sample 140S, 3.05 MPa (25%) for 100S, and 2.4 MPa (16.64%) for 60S. The greatest strength gain occurred in the sample centrifuged after 100 minutes of curing, suggesting that there may be an optimal window for centrifugation, as both insufficient and excessive pre-centrifugation curing time appear to reduce effectiveness.

Table 10: LHS liquid-solid ratio 0.3 silica modulus 1 compressive strength test results with and without centrifugation

Sample Number	Liquid/Solid	Silica Modulus	Minutes before Centrifugation	Control or Spin (C or S)	Compressive Strength(MPa)	Percent Increase in MPa from Centrifugation
LHS_0.3_1.0_140C	0.3	1.0	140	C	8.08	
LHS_0.3_1.0_140S	0.3	1.0	140	S	**9.55**	15.39
LHS_0.3_1.0_100C	0.3	1.0	100	C	9.15	
LHS_0.3_1.0_100S	0.3	1.0	100	S	**12.20**	**25**
LHS_0.3_1.0_60C	0.3	1.0	60	C	12.02	
LHS_0.3_1.0_60S	0.3	1.0	60	S	**14.42**	16.64

These findings suggest that, to preserve the optimal internal structure of centrifuged geopolymer samples made from LHS—similar to the material provided by Space Resource Technologies in February 2025—a mixture with a liquid-to-solid ratio of 0.3 and a silica modulus of 1.0 should be poured approximately 1 hour and 40 minutes prior to centrifugation.

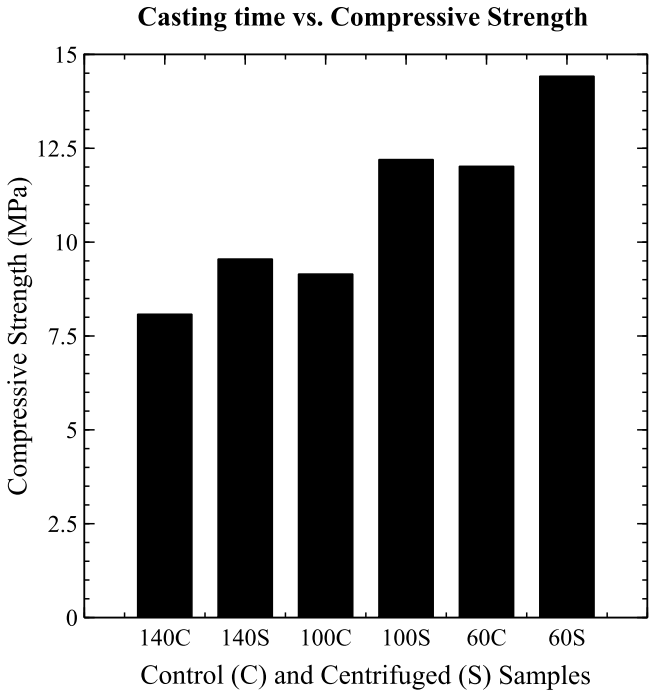

Figure 33:Bar graph of LHS liquid-solid ratio 0.3 silica modulus 1 compressive strength test results with and without centrifugation

Although 60S, seen in Figure 34, showed the highest compressive strength and second-largest improvement from centrifugation, it exhibited the lowest cohesion due to particle migration on the top surface. The top surface of all samples, centrifuged and controls alike, were indistiguishable from one another with the exception of 60S. Cohesion is paramount during curing for concrete, so the 100 minute delay samples, 100C and 100S, were considered to be the best candidates for further investigation with SEM.

Figure 34: Top surface of 60 minute delay sample after centrifugation

Researchers that attempt to replicate this experiment are likely to find variation in their findings as the regolith simulant they receive may be of a slightly different consistency and particle size distribution. If the regolith they receive is significantly more viscous when mixed into geopolymer, the curing time needed before centrifugation will likely be less. Conversely, if the geopolymer is more flowable, the time needed before centrifugation is likely to be more. These results, however, are internally consistent. While several more trails could help to provide a definitive conclusion, the evidence in this thesis is very strong that a viscous slurry of extraterrestrial simulant geopolymer allowed to cure more than an hour before centrifugation will have increased compressive strength.

5.4 Difference between LHS shipments

In Table 11 and Figure 35 are results from an ASTM Standard C109, 5 cm cube compressive strength test of samples from both shipments prepared in an identical manner. The average compressive strength of 3 samples from the February shipment is 9.75 MPa. The average compressive strength of 4 samples from the April shipment is 23.93 MPa. Evidence suggests that the particle size distribution is not consistent between the two shipments, with the April shipment having a higher proportion of fine particles than the February shipment.

Table 11: Differing compressive strengths of LHS liquid-solid ratio 0.3 silica modulus 1 from the February shipment (F1-F3) and the April shipment (A1-A4) of regolith simulant from Space Technology Resources

Sample	Liquid/Solid Ratio	Silica Modulus	Compressive Strength (MPa)
LHS_0.3_1.0_F1	0.3	1.0	8.08
LHS_0.3_1.0_F2	0.3	1.0	9.15
LHS_0.3_1.0_F3	0.3	1.0	12.02
LHS_0.3_1.0_A1	0.3	1.0	27.06
LHS_0.3_1.0_A2	0.3	1.0	17.11
LHS_0.3_1.0_A3	0.3	1.0	24.30
LHS_0.3_1.0_A4	0.3	1.0	27.23

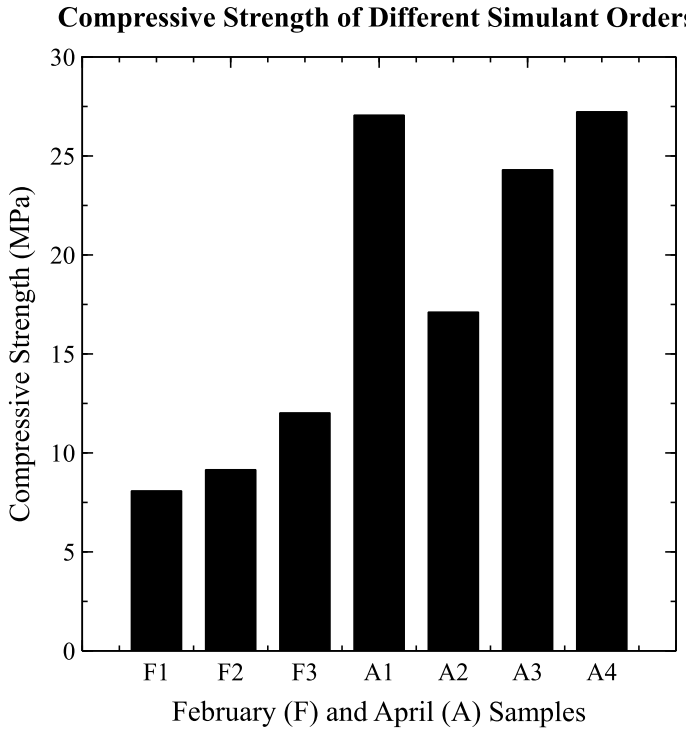

Figure 35: Bar graph of LHS liquid-solid ratio 0.3 silica modulus 1 compressive strength test results from the February shipment (F1-F3) and the April shipment (A1-A4) of regolith simulant from Space Technology Resources

SEM analysis corroborates this difference with Figure 36 showing the fine particles of the April shipment and Figure 37 showing the coarse particles of the February shipment. The fine particles allow for greater surface area for the alkali activator to loosen the chemical bonds of the minerals to facilitate geopolymerization.

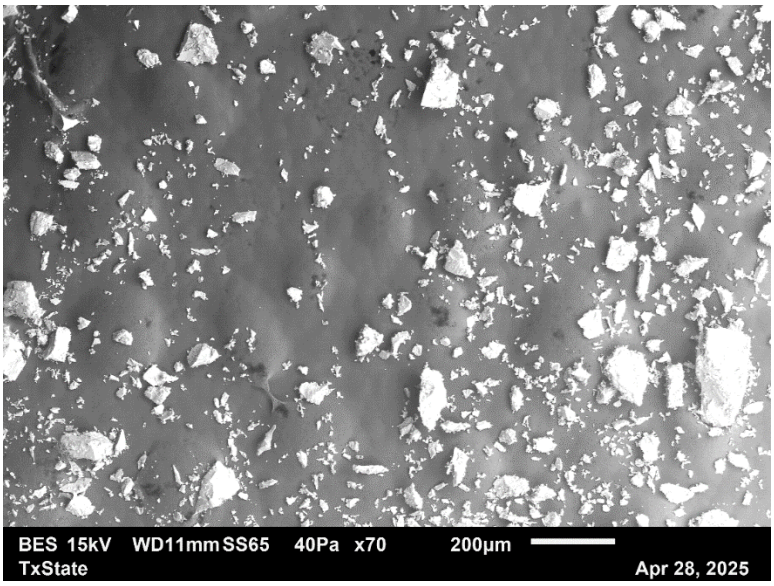

Figure 36: April Shipment of LHS exhibiting fine particles

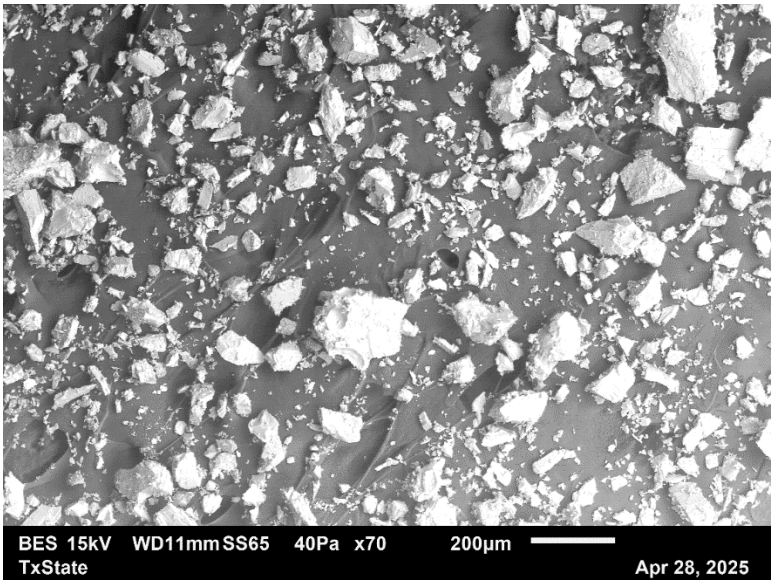

Figure 37: February shipment exhibiting coarse particles

With geopolymer from the April shipment on the left side of Figure 38, one can observe coarse particles securely surrounded by firm globules of fine paste. On the right side of Figure 38, with geopolymer made from the February shipment, one can see the effect of fewer fine particles

in the resulting concrete. Coarse particles are more dislodged and only partially connected to the fine particle paste, the greater cohesion from the April geopolymer on the left side helps to explain the higher compressive strength.

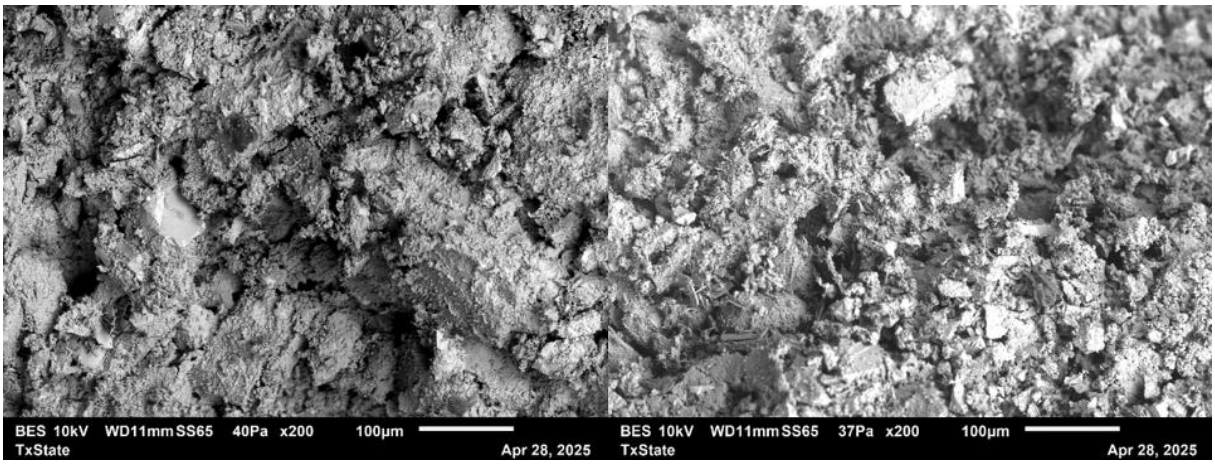

Figure 38: Surface of geopolymer of April order (left) and February order (right)

Another notable, though qualitative, indicator of variation between shipments is the difference in surface appearance and residual liquid. As shown in Figure 39, the sample prepared with the April shipment retained surface liquid, whereas the sample from the February shipment did not.

Figure 39: Recently cassted geopolymer made from the April shipment, lighter in color with more liquid (left) compared to recently poured geopolymer made from the February shipment, darker in color with less liquid (right).

This difference can be seen after curing in Figure 40. The April shipment seen on the left dried into a film which contrasts significantly from the color and consistency that can be seen in geopolymer cured from regolith simulant from the February shipment, seen on the right.

Figure 40: Film on the surface of cured and dried Geopolymer from April shipment (left) and a cured sample from the February shipment (right) that did not develop a film on the top surface

5.5 Insights gained from mixer/centrifuge prototypes

As shown in Figure 41, centrifugation produced concrete tiles in half of the mold slots, while the other half experienced leakage of alkali activator. Despite this, the prototype demonstrated the feasibility of mixing and centrifuging within the same container, though further

design improvements were required. Subsequent trials utilized a battery-powered hand-held drill for separate mixing.

Figure 41: Concrete mixer prototype with geopolymer concrete tiles

Through multiple iterations of the mixing chamber design and hands-on experimentation with the material, valuable design considerations were identified for the development of future geopolymer concrete mixers and integrated centrifuge systems. While vibration can be useful for removing entrapped air in more viscous mixtures, it may induce excessive particle size segregation in slurries with higher fluidity. While mixing the alkali activator and regolith, liquid must be

carefully contained and mixed thoroughly with the binder because if there is leakage to the outer molds before the slurry is homogeneous, proper curing cannot take place. Research on improving the design of the lunar concrete mixer continued as a senior design project focusing on the electrical engineering functionality as seen in Figure 42.

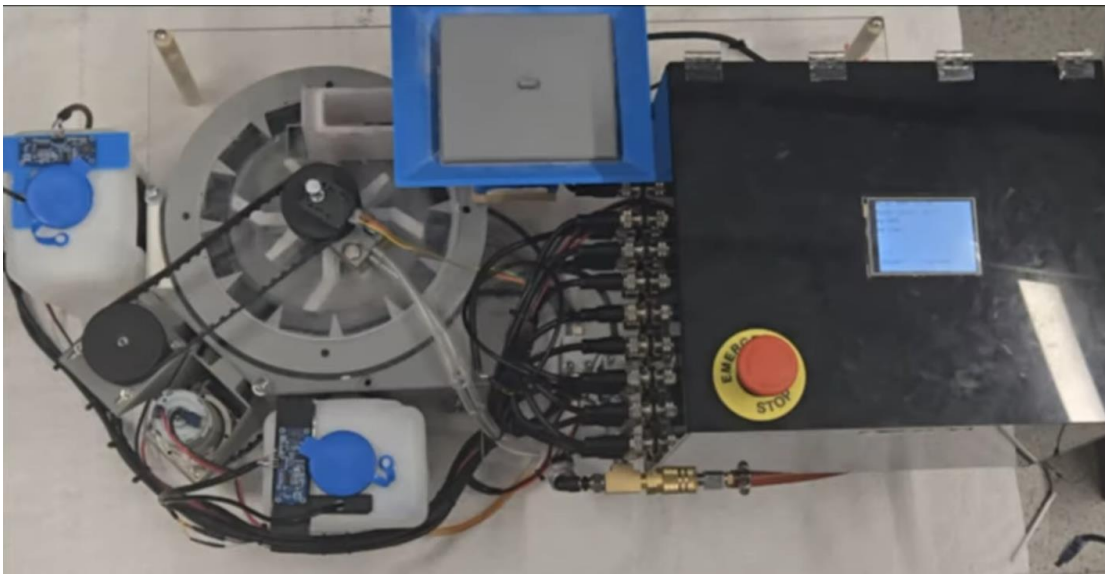

Figure 42: 2025 Bobcat CaerusCrete Lunar Regolith Simulant Geopolymer Concrete Mixer

The 2025 NASA MINDS team constructed a user interface that improves ease of operation physically and virtually with modes that are responsive to sensor data via an Arduino control system. The prototype at the time of writing, has yet to mix concrete, but is able to fully function autonomously. The team demonstrated the machine's ability to ingress material from a hopper, and liquid from a chamber, then mix the two with a central blade followed by centrifugation via a rotating chamber. The 2025 NASA MINDS team concluded that servomotors should be strong enough to overcome resistance but sensitive enough to prevent damage with sensors that can anticipate resistance and know the difference. The chamber and blades should be stainless steel to avoid breakage. Additional sealant measures should be implemented to prevent spillage, and

friction should be reduced along the interface of the mixer blade and chamber. An internal pressure washing system will be needed to clear residue from the inside of the chamber between batches of tiles produced and an egress system for these tiles also needs to be devised.

6. CONCLUSIONS

In this thesis, extraterrestrial regolith simulant geopolymer was analyzed to find the optimal mixture for centrifugation in an effort to test for an increase in compressive strength. Variants of geopolymer with different silica moduli of alkali activator and liquid-to-solid ratios were prepared, analyzed for workability, cooked at 70°C for 14 days and subjected to compressive strength tests. Based on workability and compressive strength results, a mixture was chosen to undergo centrifugation with a 13.9 gravitational equivalent force. These centrifuged samples and their corresponding control samples were fully cured, tested for compressive strength and compared. A team was also organized to prototype a concrete mixer and centrifuge designed to function in a low gravity environment. A subsequent team constructed an improved version designed to autonomously mix concrete and manufacture geopolymer tiles with a focus on the electrical engineering aspect of the machine. While challenges were encountered when separating the mixing and centrifugation processes, tiles were manufactured that could serve to function in a lunar and martian environment.

Based on the results from this study, the following conclusions were reached:

- Preliminary analysis identified particle size distribution as a key factor affecting compressive strength and influencing the workability of the regolith simulant geopolymer.
- Geopolymer mixes demonstrated a strong dependence on liquid-to-solid ratio (L/S) and silica modulus (SM) for achieving balance between extrudability and structural integrity

- Neither liquid-to-solid ratio ($p = 0.199$) nor silica modulus ($p = 0.608$) were individually significant predictors of compressive strength. However, their interaction ($p = 0.144$) showed potential relevance, suggesting that these variables should be considered jointly.
- For viscous samples, either from a high SM or low L/S, immediate vibration is recommended to remove air pockets before curing. High SM samples can solidify and become unworkable within minutes. For flowable mixes, vibration is not recommended as an excessively distinct particle size gradient can form. Prompt removal from molds, if possible without damaging the specimen, is recommended to aerate surfaces and accelerate curing.
- Centrifugation can increase the compressive strength of lunar regolith simulant geopolymer by 15-25%. For the LHS simulant from the specific shipment received by the author, along with the L/S of 0.3 and SM of 1.0 used in this study, allowing 100 minutes of curing time before centrifugation with 13.9 gravitational force equivalent units rendered optimum compressive strength increase. Individual results may vary.
- Variation may occur between shipments of regolith simulant so baseline metrics should be established so results can be compared to those of previous orders. This is to be expected as natural products can vary and discrepancies in actual regolith are likely to be found on the surface of the Moon and Mars.
- The design of a geopolymer concrete mixing and centrifugation machine must be carefully in tune with the properties of the material. Careful control of the liquid-to-solid ratio and silica modulus is essential to ensure that the mixing and forming

equipment can accommodate the resulting viscosity and workability of the wet geopolymer slurry. The speed of centrifugation is an important consideration as excessive speed results in a distinct particle size gradient which is not conducive to compressive strength, and insufficient speed will not reduce porosity.

- Timing between mixing and casting as well as centrifugation is also critical, particularly in mixtures with a high silica modulus and low liquid-to-solid ratio, as these can rapidly transition to a gelatinous and unworkable state.

Based on the findings from this study, it is concluded that LHS-1 is the most well-rounded simulant for centrifugation, with balanced reactivity, mineralogy, and particle size, making it highly suitable for mechanical strength optimization and microstructural studies. This simulant is also more efficient and reactive for alkali activation, achieving higher strengths with less silicate and lower L/S ratio. LSP-2 may require particle size refinement via sieving or activator modification for optimal geopolymer performance. Because of the lower surface area from particles larger than 1 mm, SP2 requires higher L/S ratios and an increased silica modulus to compensate for its coarser grain size and lower reactivity, but still underperforms in strength after 2 weeks of curing time. MGS-1C is extremely reactive due to its clay content and fine particle size, but its composition necessitates careful control of activator dosage and curing to mitigate large air voids, shrinkage, or strength variability. The results affirm that particle size and aluminosilicate reactivity dominate geopolymer strength trends, though alkali content and mix balance are also critical. MGS-1C is the most extrudable and highest-performing in early strength but needs efflorescence mitigation strategies (e.g., curing control, optimized activator concentration) before it can be considered to be a viable building material.

Regarding particle size distribution, for additive manufacturing, a multimodal distribution like MGS-1C with peaks around 0.02, 0.01 and 0.1 mm with the presence of both fine particles, coarser grains and a substantial fraction of intermediate sizes is favorable. For centrifuging modular building components like bricks, a unimodal particle size distribution like with LHS-1 centered around 0.07–0.09 mm, combined with a high clay content is favorable for dense packing. Based on the results of this thesis, a particle size higher than 1 mm is not recommended as the delay to curing is significant. On-site sieving and careful formulation of particle size distribution when preparing precursors for geopolymer the Moon or Mars will enhance the suitability of regolith for construction using additive manufacturing or centrifuged modular components like bricks and tiles.

On the topic of L/S ratios and SM of LHS, the following conclusions were drawn in preparing different mixtures for the purposes of this thesis. Low L/S (0.2): Mixes were generally too dry and brittle. Moderate L/S (0.25): Showed improved extrusion and handling, Higher SM values reduced workability and led to weak or brittle structures. Higher L/S (0.3): Mixes became more flowable, though prone to interlayer drying and internal dampness post-curing, Overly fluid mixtures at SM ≥ 1.5 struggled to retain shape and remained unset even after extended periods. Very High L/S (0.4): Consistently high fluidity with poor form retention across all SM levels. While overall statistical correlation between compressive strength and either L/S or SM is weak, experimental trends point to improved strength at a silica modulus near 1.5 combined with a moderate to high liquid-to-solid ratio (e.g., 0.3). These findings underscore the importance of considering interaction effects in mix design, though further testing with expanded datasets is required to validate these relationships.

Variation between shipments of regolith simulants should be carefully considered before drawing conclusions about material behavior. In practical applications on the Moon and Mars, natural heterogeneity—arising from factors such as proximity to craters, lava flows, ice deposits, erosion patterns, parent material, and solar exposure will influence regolith properties. It is essential to anticipate this variability and develop adaptable processing methods to achieve consistent and reliable performance.

6.1 Future work

Though this work proved that centrifugation could improve compressive strength in extraterrestrial regolith simulant geopolymer, variations of the experiment could take place to further understand and utilize the technique to engineer building materials in low gravity environments. Allowing the specimens to cure for 28 days would also provide more conclusive evidence to guide researchers when furthering their aims. To further prove the nature of how centrifugation might improve compressive strength, the field of space settlement would benefit from the following:

- Additional centrifugation experiments, possibly varying speed, simulant type, pre-centrifugation curing duration, liquid-to-solid ratios, and silica moduli could generate more conclusive evidence regarding improvements in compressive strength.

- Tiles could be centrifuged in a prototype like what can be seen in Figure 43, where the centrifuged tiles can undergo strength tests compared to tiles that were not centrifuged. Based on these results, different versions of the NASA MINDS concrete mixer could be prototyped to manufacture geopolymer tiles as intended, in a containment that is able to recapture and reuse water released as the concrete cures.

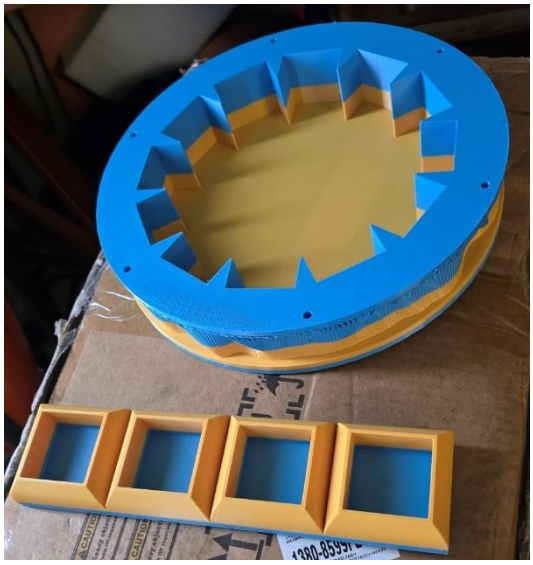

Figure 43: Prototype of concrete tile mold centrifuge along with tile mold controls for non-centrifugal curing

- Further testing the rheological properties and setting times of mixtures could take place to provide quantitative data to add to the qualitative data provided.
- A more advanced system could be developed to replicate centrifugation on the Moon or Mars, potentially through testing aboard the International Space Station. The centrifuge concept could be extended to a microgravity environment using a dual-centrifuge configuration, in which a smaller centrifuge spinning at a speed

optimized to enhance geopolymer strength is mounted onto a larger centrifuge simulating lunar or martian gravity. This nested design would enable simultaneous application of curing and environmental forces, allowing for direct comparative testing of materials under conditions that closely replicate those expected in extraterrestrial construction.

- A continuous-flow design could be considered to operate in a low gravity environment in which geopolymer slurry is centrifuged, analogous to mixing in a concrete truck, but at higher rotational speeds sufficient to eliminate air pockets prior to casting. This approach could allow the material to be directly poured into a reinforced formwork or molds, enabling the fabrication of slabs and other structural elements on the Moon and Mars.

At the time of writing, a paper is being prepared for submission to an academic journal that combines the findings of this thesis, the work of Catalina Gonzales, and forthcoming research incorporating improved methodology to produce more definitive experimental results on the topics addressed herein. Upon confirmation from NASA that a 2026 NASA MINDS competition will take place, the 2025 project lead, Reece Cavallo, is intent on advancing the work of previous teams to manufacture geopolymer tiles with an autonomously operating machine.

The ultimate future work of the ideas laid out in this thesis would be humans manufacturing regolith geopolymer far from their home planet. It is the hope of all the contributors of this work, the founders of which can be seen in Figure 44, that this work continues. The author and those who helped him hope that eventually concrete enhances the quality of life for people on the Moon

and Mars, who will one day look up in the sky towards people on Earth who also enjoy their days and nights on top of concrete foundations.

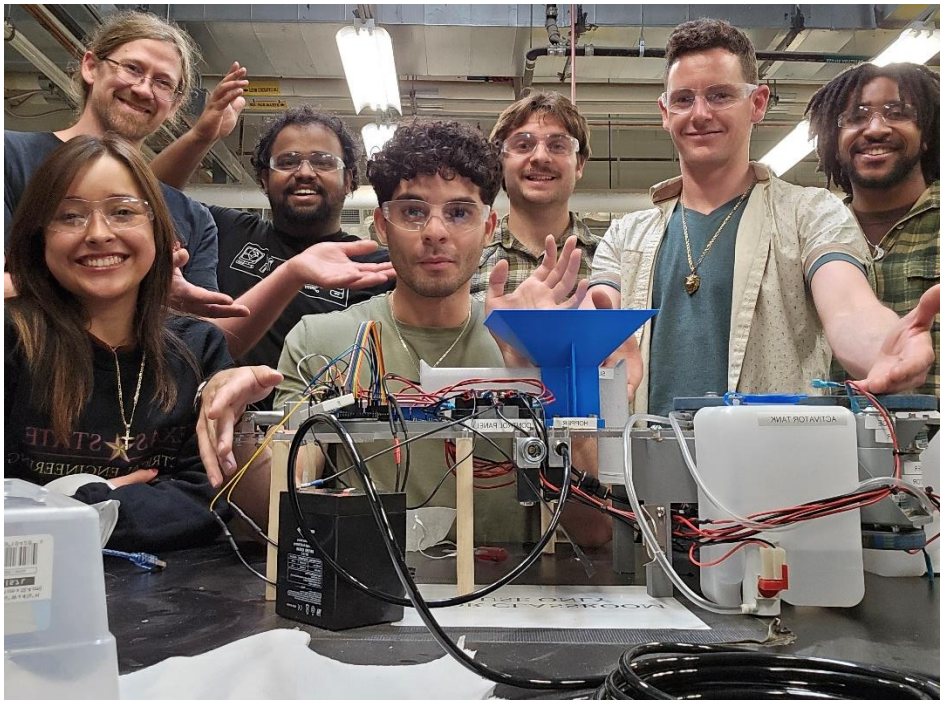

Figure 44: Texas State University Bobcat CaerusCrete NASA MINDS Team (from left to right) Daniella Salazar, Joseph Ely, Venkatasiva Somayajula, Ali Kobeissi, Reece Cavallo, Dylan Depew, Jamal Close

APPENDIX

	Liquid/Solid Ratio	Designed silica modulus	NaOH solution (g)	Sodium Silicate solution (g)	Additional SiO2 to add (g)	Simulant (g)
LHS_0.2_1.0	0.2	1	14.31	16.67	5.96	100
LHS_0.2_1.5	0.2	1.5	19.07	11.11	8.67	100
LHS_0.2_2.0	0.2	2	9.54	22.22	15.18	100
LHS_0.25_1.0	0.25	1	17.88	20.83	7.45	100
LHS_0.25_1.5	0.25	1.5	23.84	13.89	10.84	100
LHS_0.25_2.0	0.25	2	11.92	27.78	18.98	100
LHS_0.3_1.0	0.3	1	21.46	25.00	8.94	100
LHS_0.3_1.5	0.3	1.5	28.61	16.67	13.01	100
LHS_0.3_2.0	0.3	2	14.31	33.33	22.77	100
LHS_0.4_1.0	0.4	1	28.61	33.33	11.92	100
LHS_0.4_1.5	0.4	1.5	38.15	22.22	17.35	100
LHS_0.4_2.0	0.4	2	19.07	44.44	30.37	100
SP2_0.2_1.0	0.2	1	14.31	16.67	5.96	100
SP2_0.2_1.5	0.2	1.5	19.07	11.11	8.67	100
SP2_0.2_2.0	0.2	2	9.54	22.22	15.18	100
SP2_0.25_1.0	0.25	1	17.88	20.83	7.45	100
SP2_0.25_1.5	0.25	1.5	23.84	13.89	10.84	100
SP2_0.25_2.0	0.25	2	11.92	27.78	18.98	100
SP2_0.3_1.0	0.3	1	21.46	25.00	8.94	100
SP2_0.3_1.5	0.3	1.5	28.61	16.67	13.01	100
SP2_0.3_2.0	0.3	2	14.31	33.33	22.77	100
SP2_0.4_1.0	0.4	1	28.61	33.33	11.92	100
SP2_0.4_1.5	0.4	1.5	38.15	22.22	17.35	100
SP2_0.4_2.0	0.4	2	19.07	44.44	30.37	100
MGS_0.4_1.0	0.4	1	28.61	33.33	11.92	100
MGS_0.4_1.5	0.4	1.5	38.15	22.22	17.35	100
MGS_0.4_2.0	0.4	2	19.07	44.44	30.37	100
MGS_0.4_2.5	0.4	2.5	38.15	22.22	32.23	100
MGS_0.4_3.0	0.4	3	19.07	44.44	46.79	100

Appendix 1: Proportions and masses of reagents of the Alkali Activator Mixture proportionally for 100g of LHS, SP2 and MGS-1C simulant

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